ACRP

REPORT 97

AIRPORT COOPERATIVE RESEARCH PROGRAM

Sponsored by the Federal Aviation Administration

Measuring PM Emissions from Aircraft Auxiliary Power Units, Tires, and Brakes

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

ACRP OVERSIGHT COMMITTEE*

CHAIR

James Wilding
Metropolitan Washington Airports Authority (retired)

VICE CHAIR

Jeff Hamiel
Minneapolis–St. Paul Metropolitan Airports Commission

MEMBERS

James Crites
Dallas–Fort Worth International Airport
Richard de Neufville
Massachusetts Institute of Technology
Kevin C. Dolliole
Unison Consulting
John K. Duval
Austin Commercial, LP
Kitty Freidheim
Freidheim Consulting
Steve Grossman
Jacksonville Aviation Authority
Kelly Johnson
Northwest Arkansas Regional Airport Authority
Catherine M. Lang
Federal Aviation Administration
Gina Marie Lindsey
Los Angeles World Airports
Carolyn Motz
Airport Design Consultants, Inc.
Richard Tucker
Huntsville International Airport

EX OFFICIO MEMBERS

Paula P. Hochstetler
Airport Consultants Council
Sabrina Johnson
U.S. Environmental Protection Agency
Richard Marchi
Airports Council International—North America
Laura McKee
Airlines for America
Henry Ogrodzinski
National Association of State Aviation Officials
Melissa Sabatine
American Association of Airport Executives
Robert E. Skinner, Jr.
Transportation Research Board

SECRETARY

Christopher W. Jenks
Transportation Research Board

*Membership as of March 2012.

TRANSPORTATION RESEARCH BOARD 2013 EXECUTIVE COMMITTEE*

OFFICERS

CHAIR: **Deborah H. Butler,** *Executive Vice President, Planning, and CIO, Norfolk Southern Corporation, Norfolk, VA*
VICE CHAIR: **Kirk T. Steudle,** *Director, Michigan DOT, Lansing*
EXECUTIVE DIRECTOR: **Robert E. Skinner, Jr.,** *Transportation Research Board*

MEMBERS

Victoria A. Arroyo, *Executive Director, Georgetown Climate Center, and Visiting Professor, Georgetown University Law Center, Washington, DC*
Scott E. Bennett, *Director, Arkansas State Highway and Transportation Department, Little Rock*
William A. V. Clark, *Professor of Geography (emeritus) and Professor of Statistics (emeritus), Department of Geography, University of California, Los Angeles*
James M. Crites, *Executive Vice President of Operations, Dallas–Fort Worth International Airport, TX*
Malcolm Dougherty, *Director, California Department of Transportation, Sacramento*
John S. Halikowski, *Director, Arizona DOT, Phoenix*
Michael W. Hancock, *Secretary, Kentucky Transportation Cabinet, Frankfort*
Susan Hanson, *Distinguished University Professor Emerita, School of Geography, Clark University, Worcester, MA*
Steve Heminger, *Executive Director, Metropolitan Transportation Commission, Oakland, CA*
Chris T. Hendrickson, *Duquesne Light Professor of Engineering, Carnegie Mellon University, Pittsburgh, PA*
Jeffrey D. Holt, *Managing Director, Bank of Montreal Capital Markets, and Chairman, Utah Transportation Commission, Huntsville, UT*
Gary P. LaGrange, *President and CEO, Port of New Orleans, LA*
Michael P. Lewis, *Director, Rhode Island DOT, Providence*
Joan McDonald, *Commissioner, New York State DOT, Albany*
Donald A. Osterberg, *Senior Vice President, Safety and Security, Schneider National, Inc., Green Bay, WI*
Steve Palmer, *Vice President of Transportation, Lowe's Companies, Inc., Mooresville, NC*
Sandra Rosenbloom, *Director, Innovation in Infrastructure, The Urban Institute, Washington, DC*
Henry G. (Gerry) Schwartz, Jr., *Chairman (retired), Jacobs/Sverdrup Civil, Inc., St. Louis, MO*
Kumares C. Sinha, *Olson Distinguished Professor of Civil Engineering, Purdue University, West Lafayette, IN*
Daniel Sperling, *Professor of Civil Engineering and Environmental Science and Policy; Director, Institute of Transportation Studies; University of California, Davis*
Gary C. Thomas, *President and Executive Director, Dallas Area Rapid Transit, Dallas, TX*
Paul Trombino III, *Director, Iowa DOT, Ames*
Phillip A. Washington, *General Manager, Regional Transportation District, Denver, CO*

EX OFFICIO MEMBERS

Rebecca M. Brewster, *President and COO, American Transportation Research Institute, Marietta, GA*
Anne S. Ferro, *Administrator, Federal Motor Carrier Safety Administration, U.S. DOT*
John T. Gray II, *Senior Vice President, Policy and Economics, Association of American Railroads, Washington, DC*
Michael P. Huerta, *Administrator, Federal Aviation Administration, U.S. DOT*
Paul N. Jaenichen, Sr., *Acting Administrator, Maritime Administration, U.S. DOT*
Michael P. Melaniphy, *President and CEO, American Public Transportation Association, Washington, DC*
Victor M. Mendez, *Administrator, Federal Highway Administration, U.S. DOT*
Robert J. Papp (Adm., U.S. Coast Guard), *Commandant, U.S. Coast Guard, U.S. Department of Homeland Security*
Lucy Phillips Priddy, *Research Civil Engineer, U.S. Army Corps of Engineers, Vicksburg, MS, and Chair, TRB Young Members Council, Washington, DC*
Cynthia L. Quarterman, *Administrator, Pipeline and Hazardous Materials Safety Administration, U.S. DOT*
Peter M. Rogoff, *Administrator, Federal Transit Administration, U.S. DOT*
Craig A. Rutland, *U.S. Air Force Pavement Engineer, Air Force Civil Engineer Center, Tyndall Air Force Base, FL*
David L. Strickland, *Administrator, National Highway Traffic Safety Administration, U.S. DOT*
Joseph C. Szabo, *Administrator, Federal Railroad Administration, U.S. DOT*
Polly Trottenberg, *Under Secretary for Policy, U.S. DOT*
Robert L. Van Antwerp (Lt. General, U.S. Army), *Chief of Engineers and Commanding General, U.S. Army Corps of Engineers, Washington, DC*
Barry R. Wallerstein, *Executive Officer, South Coast Air Quality Management District, Diamond Bar, CA*
Gregory D. Winfree, *Acting Administrator, Research and Innovative Technology Administration, U.S. DOT*
Frederick G. (Bud) Wright, *Executive Director, American Association of State Highway and Transportation Officials, Washington, DC*

*Membership as of September 2013.

AIRPORT COOPERATIVE RESEARCH PROGRAM

ACRP REPORT 97

Measuring PM Emissions from Aircraft Auxiliary Power Units, Tires, and Brakes

Prem Lobo
Philip D. Whitefield
Donald E. Hagen
MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY
CENTER OF EXCELLENCE FOR AEROSPACE PARTICULATE EMISSIONS REDUCTION RESEARCH
Rolla, MO

IN ASSOCIATION WITH

Richard C. Miake-Lye
Scott C. Herndon
Jonathan P. Franklin
Edward C. Fortner
Michael T. Timko
AERODYNE RESEARCH, INC.
Billerica, MA

W.B. Knighton
MONTANA STATE UNIVERSITY
Bozeman, MT

Sandy Webb
ENVIRONMENTAL CONSULTING GROUP, LLC
Annapolis, MD

Raymond J. Hoffelt
CITY OF CHICAGO
Chicago, IL

Subscriber Categories
Aviation • Environment

Research sponsored by the Federal Aviation Administration

TRANSPORTATION RESEARCH BOARD

WASHINGTON, D.C.
2013
www.TRB.org

AIRPORT COOPERATIVE RESEARCH PROGRAM

Airports are vital national resources. They serve a key role in transportation of people and goods and in regional, national, and international commerce. They are where the nation's aviation system connects with other modes of transportation and where federal responsibility for managing and regulating air traffic operations intersects with the role of state and local governments that own and operate most airports. Research is necessary to solve common operating problems, to adapt appropriate new technologies from other industries, and to introduce innovations into the airport industry. The Airport Cooperative Research Program (ACRP) serves as one of the principal means by which the airport industry can develop innovative near-term solutions to meet demands placed on it.

The need for ACRP was identified in *TRB Special Report 272: Airport Research Needs: Cooperative Solutions* in 2003, based on a study sponsored by the Federal Aviation Administration (FAA). The ACRP carries out applied research on problems that are shared by airport operating agencies and are not being adequately addressed by existing federal research programs. It is modeled after the successful National Cooperative Highway Research Program and Transit Cooperative Research Program. The ACRP undertakes research and other technical activities in a variety of airport subject areas, including design, construction, maintenance, operations, safety, security, policy, planning, human resources, and administration. The ACRP provides a forum where airport operators can cooperatively address common operational problems.

The ACRP was authorized in December 2003 as part of the Vision 100-Century of Aviation Reauthorization Act. The primary participants in the ACRP are (1) an independent governing board, the ACRP Oversight Committee (AOC), appointed by the Secretary of the U.S. Department of Transportation with representation from airport operating agencies, other stakeholders, and relevant industry organizations such as the Airports Council International-North America (ACI-NA), the American Association of Airport Executives (AAAE), the National Association of State Aviation Officials (NASAO), Airlines for America (A4A), and the Airport Consultants Council (ACC) as vital links to the airport community; (2) the TRB as program manager and secretariat for the governing board; and (3) the FAA as program sponsor. In October 2005, the FAA executed a contract with the National Academies formally initiating the program.

The ACRP benefits from the cooperation and participation of airport professionals, air carriers, shippers, state and local government officials, equipment and service suppliers, other airport users, and research organizations. Each of these participants has different interests and responsibilities, and each is an integral part of this cooperative research effort.

Research problem statements for the ACRP are solicited periodically but may be submitted to the TRB by anyone at any time. It is the responsibility of the AOC to formulate the research program by identifying the highest priority projects and defining funding levels and expected products.

Once selected, each ACRP project is assigned to an expert panel, appointed by the TRB. Panels include experienced practitioners and research specialists; heavy emphasis is placed on including airport professionals, the intended users of the research products. The panels prepare project statements (requests for proposals), select contractors, and provide technical guidance and counsel throughout the life of the project. The process for developing research problem statements and selecting research agencies has been used by TRB in managing cooperative research programs since 1962. As in other TRB activities, ACRP project panels serve voluntarily without compensation.

Primary emphasis is placed on disseminating ACRP results to the intended end-users of the research: airport operating agencies, service providers, and suppliers. The ACRP produces a series of research reports for use by airport operators, local agencies, the FAA, and other interested parties, and industry associations may arrange for workshops, training aids, field visits, and other activities to ensure that results are implemented by airport-industry practitioners.

ACRP REPORT 97

Project 02-17
ISSN 1935-9802
ISBN 978-0-309-28371-7
Library of Congress Control Number 2013954863

COPYRIGHT INFORMATION

NOTICE

The project that is the subject of this report was a part of the Airport Cooperative Research Program, conducted by the Transportation Research Board with the approval of the Governing Board of the National Research Council.

The members of the technical panel selected to monitor this project and to review this report were chosen for their special competencies and with regard for appropriate balance. The report was reviewed by the technical panel and accepted for publication according to procedures established and overseen by the Transportation Research Board and approved by the Governing Board of the National Research Council.

The opinions and conclusions expressed or implied in this report are those of the researchers who performed the research and are not necessarily those of the Transportation Research Board, the National Research Council, or the program sponsors.

The Transportation Research Board of the National Academies, the National Research Council, and the sponsors of the Airport Cooperative Research Program do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of the report.

Published reports of the

AIRPORT COOPERATIVE RESEARCH PROGRAM

are available from:

Transportation Research Board
Business Office
500 Fifth Street, NW
Washington, DC 20001

and can be ordered through the Internet at

http://www.national-academies.org/trb/bookstore

Printed in the United States of America

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. On the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. C. D. Mote, Jr., is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, on its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. C. D. Mote, Jr., are chair and vice chair, respectively, of the National Research Council.

The **Transportation Research Board** is one of six major divisions of the National Research Council. The mission of the Transportation Research Board is to provide leadership in transportation innovation and progress through research and information exchange, conducted within a setting that is objective, interdisciplinary, and multimodal. The Board's varied activities annually engage about 7,000 engineers, scientists, and other transportation researchers and practitioners from the public and private sectors and academia, all of whom contribute their expertise in the public interest. The program is supported by state transportation departments, federal agencies including the component administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation. **www.TRB.org**

www.national-academies.org

COOPERATIVE RESEARCH PROGRAMS

CRP STAFF FOR ACRP REPORT 97

Christopher W. Jenks, *Director, Cooperative Research Programs*
Crawford F. Jencks, *Deputy Director, Cooperative Research Programs*
Michael R. Salamone, *ACRP Manager*
Joseph D. Navarrete, *Senior Program Officer*
Terri Baker, *Senior Program Assistant*
Eileen P. Delaney, *Director of Publications*
Kami Cabral, *Editor*

ACRP PROJECT 02-17 PANEL
Field of Environment

Brian Y. Kim, *Wyle, Arlington, VA* (Chair)
Giday A. Girmay, *Boeing Commercial Airplanes, Seattle, WA*
Michael Kenney, *KB Environmental Sciences, Inc., St. Petersburg, FL*
Mark Kunugi, *Unicircuit, Denver, CO*
Todd H. Welty, *Reno-Tahoe Airport Authority, Reno, NV*
Chowen Chou Wey, *Army Research Laboratory, Adelphi, MD*
Carl Ma, *FAA Liaison*
Christine Gerencher, *TRB Liaison*

AUTHOR ACKNOWLEDGMENTS

The research reported herein was performed under ACRP Project 02-17 by the Missouri University of Science and Technology Center of Excellence for Aerospace Particulate Emissions Reduction Research; Aerodyne Research, Inc.; Montana State University; and Environmental Consulting Group, LLC. The Missouri University of Science and Technology served as the primary contractor.

The project team gratefully acknowledges the assistance of United Airlines staff, including Roger E. Peterson, the Senior Manager of Operations Technical Support, and Harold H. Roehrich. For the coordination of the APU measurements the assistance of David Nosek was vital. The project team would also like to thank "Jonathan, Jim, and Gus" for helping with the B767 and B777 despite the cold, and "Perry, Scott, and Billy" for lining up the series of A320s at the hangar. The project team is grateful to Dieter "DJ" Holz for chaperoning the truck through the terminal area tests.

Special thanks to Alfonso Perez with O'Hare Airport Operations Staff for securing permission to bring the personnel and instruments to the airport.

FOREWORD

By Joseph D. Navarrete
Staff Officer
Transportation Research Board

ACRP Report 97: Measuring PM Emissions from Aircraft Auxiliary Power Units, Tires, and Brakes presents the results of a comprehensive test program designed to measure particulate matter (PM) emissions from auxiliary power units (APUs) and from tires and brakes during the landing phase of operation of in-service commercial aircraft. While significant emissions data exist for aircraft main engines, only limited data have been available for APUs, and no data existed for PM emissions produced during landing by tires and brakes. The research results, therefore, provide a significant contribution to the characterization of emissions from these sources. The data obtained from the test program were used to develop PM emission indices for APUs and tires. Providing such data will allow airports to improve the accuracy of their PM emissions inventories.

Assessment of PM emissions from aircraft operations at airports is growing in importance as demand for air travel increases, and modeling is often used to estimate emissions due to aviation activity. Although there is increasing information on aircraft main engine PM emissions, little or no PM data are available for on-aircraft APU emissions, or tire and brake emissions during landing operations. To address this lack of data, a measurement campaign for quantifying and characterizing PM emissions from these sources was undertaken.

The research, led by the Missouri University of Science and Technology Center of Excellence for Aerospace Particulate Emissions Reduction Research, began with developing sampling and measurement techniques. These techniques were then applied at a large commercial airport that was selected based on several factors, including access to a representational aircraft fleet mix, varied meteorology, and airfield accessibility. Two measurement campaigns, one conducted in late winter and one conducted in the summer, allowed the researchers to evaluate the impact of weather on these emissions sources. Emissions factors were then computed based on the data. The resulting factors, presented in this report, are now available for use in air quality models.

Chapter 1 provides an introduction to the study. A description of the research plan, including the sampling protocol, instrumentation, measurement, and analysis is provided in Chapter 2. Conclusions and suggestions for future research are provided in Chapter 3. A bibliography and a glossary are also provided. Appendix A describes related literature and includes an annotated bibliography. Appendix B describes the process for selecting the study airport and airline.

Notable findings show that new technology APUs produce lower PM emissions compared with older models and that, on a mass basis, less than 1 percent of total PM emissions during landing come from the aircraft tires (i.e., the traditional puff of smoke seen at

touchdown). While it was not feasible to compute a PM emissions index for aircraft brakes, the data suggest that the contribution of brake PM to overall PM at the study airport is negligible. These findings represent a significant contribution to the current state of the art in airport emissions assessment.

CONTENTS

SUMMARY

Measuring PM Emissions from Aircraft Auxiliary Power Units, Tires, and Brakes

In the past decade, air quality around airports has been studied for regulatory, environmental, and human health purposes. Significant effort and expense have been invested in measuring and analyzing the primary sources of emissions at airports such as aircraft main engines, ground support equipment, buses and shuttles, and passenger vehicles. This project measured emissions from aircraft auxiliary power units (APUs), aircraft tires, and brakes for the first time to complete the definition and characterization of key airport emissions sources.

After conducting an extensive review of candidate airports for hosting the APU, tires, and brakes emissions measurement campaign, Chicago O'Hare International Airport (ORD) and United Airlines were selected. Several factors, such as size and fleet mix, meteorology, prior experience of team members working with specific airports, and accessibility, were considered during the review process and used to down-select a preferred airport and airline.

Two measurement campaigns were conducted: a winter campaign (March 2011) and a summer campaign (August 2011). These campaigns allowed the research team to emphasize certain sources in each campaign, testing and then implementing measurement protocols for previously untested sources. They also provided varying ambient conditions to evaluate the impact of metrological factors on these emissions sources. APUs were the primary focus of the winter campaign with preliminary testing of tires and brakes to develop those measurement protocols. The summer campaign focused greater effort on collecting emissions data from tires and brakes.

APU emissions were determined to be very similar to larger aircraft jet engines, which they closely resemble in design and operation. In the past, emission studies that included APUs relied on a very limited set of data from older design APUs. Data from this project confirmed that APU particulate matter (PM) emissions from in-service engines are much lower than expected based on that prior data. Emission indices, comparable to those used in advanced emissions models, were computed for three APUs, which are representative of the current technology most commonly found in the U.S. commercial airline fleet. The indices were computed at the three operational power settings—idle (no load), both packs (environmental control condition), and motoring engine (main engine start). It was determined that the more modern technology APU has the lowest number and mass-based emission indices among the three APU technologies investigated during this study.

Emissions measurements from tires during aircraft landing events determined that particles are emitted when aircraft land, characterized by a puff of smoke. More than 100 aircraft landings were monitored and measurements collected from 23 aircraft landings were used to characterize tire emissions. On a mass basis, less than 1% of total PM emitted during a Landing Take-off (LTO) cycle comes from the aircraft tires. Notably, little or no PM is emitted when aircraft land on a wet runway.

Several emission plumes were sampled during the braking phase of landing aircraft. No distinct emission signatures from aircraft brakes were discernible and it is not feasible to compute a PM emissions index for aircraft brakes. However, the data analyzed suggests that contribution of brake PM to overall PM inventory at this particular airport is negligible.

As a significant contribution to the current state of the art in airport emissions assessment, PM emission indices were determined for APUs and tires. The research team anticipates that these PM emission indices will be incorporated into current models used for airport air quality studies. Providing such data will allow airports to improve the accuracy of their PM emissions inventories and better prioritize their emission mitigation efforts.

CHAPTER 1

Introduction

Airports today are modernizing and expanding to meet the needs of the flying public as demand for air transportation grows. As airport activity increases, so do potential environmental impacts. For that reason airports must be vigilant to ensure they comply with all regulatory requirements. Similarly, policy makers must determine whether air emissions associated with aviation need to be mitigated; to what extent, if any, reductions need to be made to protect the public and natural environment; and how, where, when, and by whom this will be accomplished. A great deal of data on emissions sources at airports has been developed within the past several years (Webb et al. 2008, Whitefield et al. 2008, Herndon et al. 2012, Kim et al. 2008, Lobo et al. 2007a). However, there has been insufficient information to adequately characterize emissions of particulate matter (PM) from some of the emissions sources commonly found at airports, notably auxiliary power units (APUs), tires, and brakes (Webb et al. 2008).

This project developed sampling and measurement techniques appropriate for emissions measurements of aircraft APUs, tires, and brakes and then applied these techniques in two major measurement campaigns at an airport. This report describes and summarizes the project results, which can be used directly in emissions modeling or to supplement airport emissions studies. Such data will allow airports to improve the accuracy of their PM emissions inventories and better prioritize their emissions mitigation efforts.

1.1 Project Work Plan

After conducting an extensive review of candidate airports for hosting the APU, tires, and brakes emissions measurement campaign, Chicago O'Hare International Airport (ORD) was selected. Several factors, such as size and fleet mix, meteorology, prior experience of team members working with specific airports, and accessibility, were considered during the review process and used to down-select a preferred airport. A somewhat similar process was followed to select an airline to collaborate with on this project, based on fleet mix, prior working experience, and significant presence at the airport. The results of this review process and the selection of ORD and United Airlines (UAL) is described in Appendix B.

Two measurement campaigns were conducted: a winter campaign (March 2011) and a summer campaign (August 2011). These campaigns allowed the research team to emphasize certain sources in each campaign, testing and then implementing measurement protocols for previously untested sources. They also provided varying ambient conditions to evaluate the impact of weather on these emissions sources. APUs were the primary focus of the winter campaign with preliminary testing of tires and brakes to develop those measurement protocols. The summer campaign focused greater effort on collecting emissions data from tires and brakes.

The data that was collected during the two measurement campaigns was analyzed for each of the sources. Emissions factors, normalized to mass of fuel burned for APUs and landings for tires, were computed based on the data. The resulting emissions factors are now available for analysts to use in models such as the Federal Aviation Administration's (FAA's) Aviation Environmental Design Tool (AEDT).

1.2 Report Organization

Following this Chapter 1 introduction, Chapter 2 describes the research plan in detail and includes descriptions of the sampling protocol, instrumentation, measurements, and PM emissions analysis for APUs, tires, and brakes. Chapter 3 presents conclusions that are drawn based on the project analytical results, and suggestions for future research are described. Supporting information is provided, including a glossary of terms, acronyms, and abbreviations. Appendix A describes the project literature and includes an annotated bibliography. Appendix B describes the process by which ORD and UAL were selected as essential project partners.

CHAPTER 2

Research Approach

2.1 Test Site Description

2.1.1 Winter 2011 Study at Chicago O'Hare International Airport

The winter study was conducted during March 7–11, 2011, at the Chicago O'Hare International Airport. Table 1 contains a summary of measurements obtained during the winter study.

PM emissions from in-service commercial APUs from the fleet of UAL were measured on March 8, 2011. The first round of testing occurred near the maintenance hangar of UAL and the second round was conducted in the terminal area where the aircraft were parked at the gate. Tire and brake emissions were studied near runways on March 9–11. Figure 1 shows the GPS trace of the location of the Aerodyne mobile laboratory (mobile laboratory) and the location of various test sites that were used during the winter study.

ORD Airport Operations was able to work in conjunction with terminal area controllers to escort the mobile laboratory while on the secure side of the airport property. The fundamental premise of the tire and brake measurement approach is to maneuver downwind from the emissions source of interest. The use of instrumentation with fast measurement rates (1 second) enables the emissions source (e.g., the touchdown plume) to be characterized as a transient perturbation above background. For example, when the prevailing wind was from out of the north and northwest, the mobile laboratory was positioned on the downwind side of Runway 28 near the touchdown area (noted as Touchdown28 in Figure 1) for the touchdown/tire measurements. This runway was also used for departing aircraft; however, the ensemble of instrumentation unambiguously identifies the takeoff engine emissions distinctly from the tire and brake emissions.

2.1.2 Summer 2011 Study at Chicago O'Hare International Airport

The second measurement campaign was conducted during August 22–26, 2011, at the Chicago O'Hare International Airport. Table 2 contains a summary of measurements taken during the study.

Figure 2 shows the GPS trace of the location of the Aerodyne mobile at the Chicago O'Hare International Airport during the summer study.

The mobile laboratory was escorted to areas very close to the active runway (Runway 10-28). The pink boxes in Figure 3 represent the positions where the mobile laboratory was parked for in situ sampling of aircraft PM brake and tire emissions downwind of the active runway. Arrows represent the approximate sampling vector for each sampling position. Sampling distances ranged from 100 m to 1,100 m, depending on the location of the mobile laboratory and the prevailing wind direction.

2.1.2.1 GPS Location of the 10-Pad Sampling Site

During an afternoon period, the prevailing wind direction was from the south-southeast. The mobile laboratory sampled from the location depicted at the 10-Pad (Figure 4), the large aircraft holding area adjacent to Runway 10-28. Aircraft were landing from the west and they typically crossed the upwind vector at approximately 424.5 km easting during this period. This sampling vector was well after the touchdown zone (423–424 km easting in the figure) and, as a result, no tire plumes were observed. Only plumes attributed to reverse thrust were observed at the 10-Pad location.

2.1.2.2 GPS Location for Three Different Days

The different colored points in Figure 5 denote different days of sampling. During PM emissions measurements on these days, aircraft were landing from the east. On the day denoted by the red diamonds, the prevailing wind was from the north-northwest. The aircraft plumes sampled on this day were characterized by the PM signatures associated with abraded tire emissions. On the day denoted by the blue diamonds, the winds were from the northwest. The focus on this day was to collect brake emissions at different lengths

Table 1. Summary of measurements obtained during the winter study.

Date	*Activity*	*Location*	*Temp Range (°F)*
March 7, 2011	Setup	UAL Hangar	24–34
March 8, 2011	APU Emissions Measurements	UAL Hangar/ Terminal Area	32–45
March 9, 2011	Tire Emissions Measurements	Runway	33–44
March 10, 2011	Tire Emissions Measurements	Runway	32–37
March 11, 2011	Tire and Brake Emissions Measurements	Runway	27–47

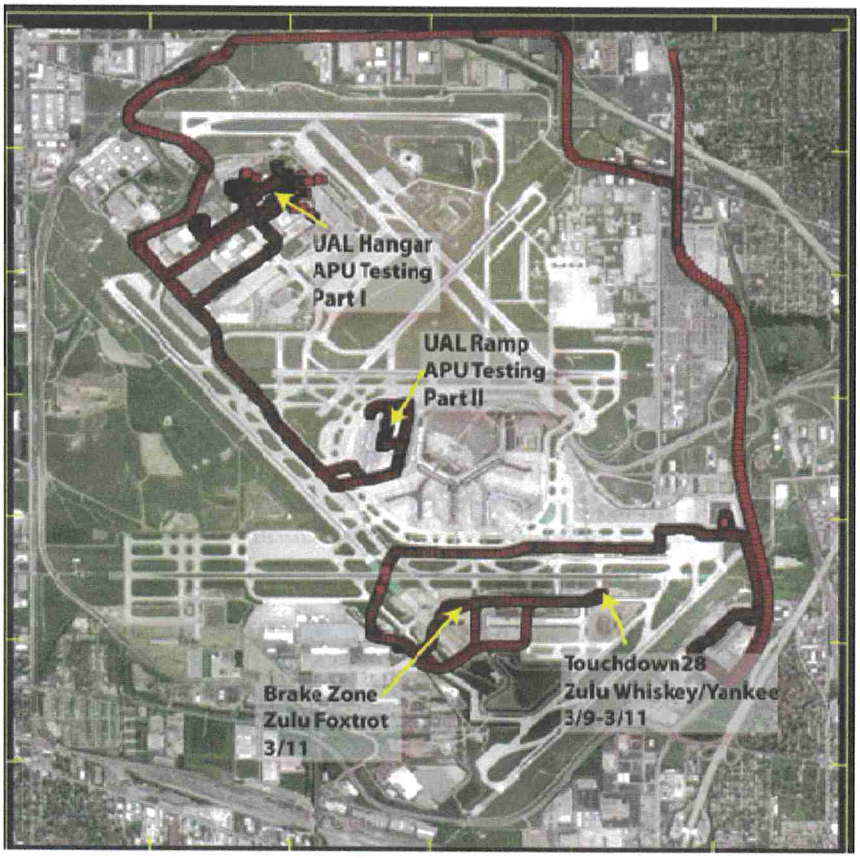


Figure 1. GPS trace of the location of the Aerodyne mobile laboratory and location of test sites for PM emissions measurements of APUs, tires, and brakes during the winter study.

Table 2. Summary of measurements obtained during the summer study.

Date	*Activity*	*Temp Range (°F)*
August 22, 2011	Setup and Brake Emissions measurements	59–82
August 23, 2011	Brake Emissions measurements	62–73
August 24, 2011	Tire and Brake Emissions measurements	69–92
August 25, 2011	Tire and Brake Emissions measurements	64–83
August 26, 2011	Brake Emissions measurements	59–83

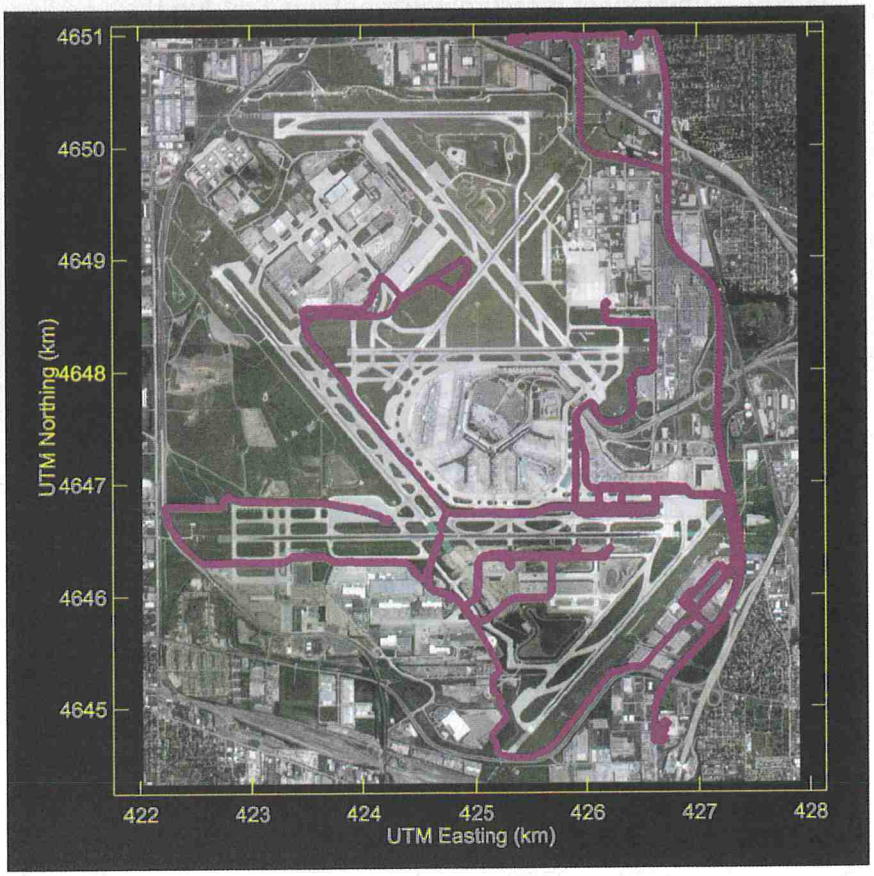


Figure 2. GPS trace of the Aerodyne mobile laboratory overlaid on top of the image of O'Hare International Airport during the summer study.

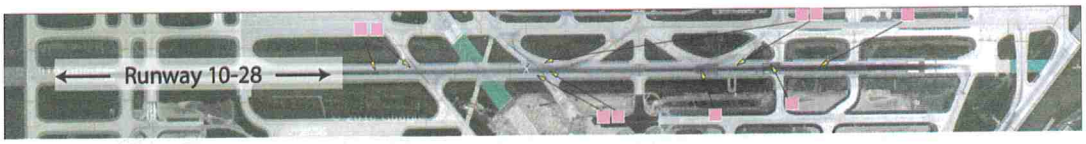


Figure 3. Locations of sampling positions of the mobile laboratory during the summer study.

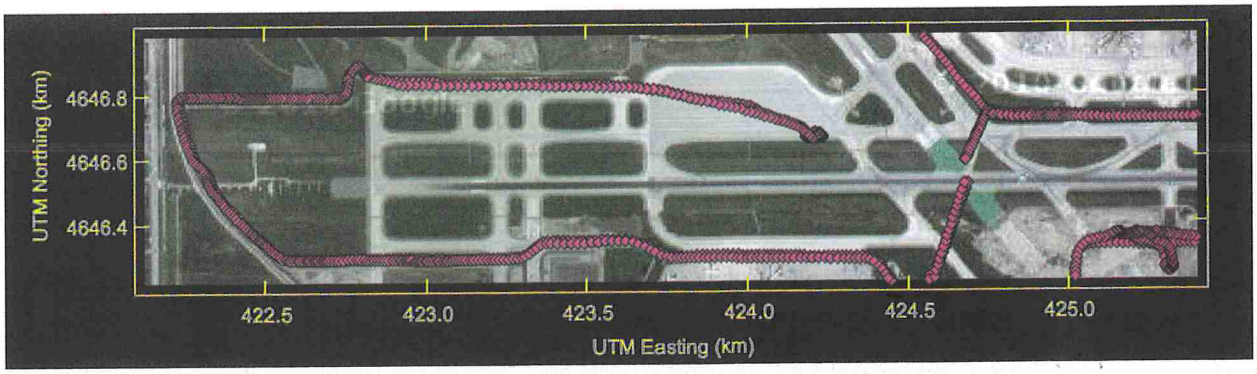


Figure 4. GPS trace of the mobile laboratory at the 10-Pad sampling site.

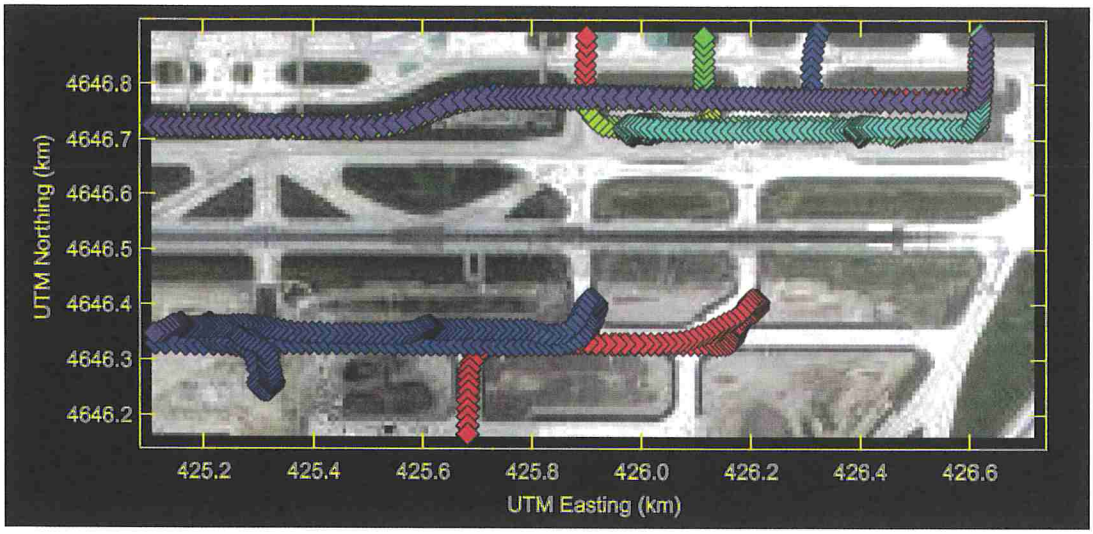


Figure 5. GPS trace of the mobile laboratory for tire and brake emissions measurements.

down the touchdown roll. On the days denoted by the green and *cyan colored diamonds*, the wind was from the south-southeast and southeast, respectively. The plumes analyzed on these days contained some tire characteristics, reverse thrust, and the likely onset of braking.

2.2 Sampling, Measurement, and Analysis Plan

2.2.1 Sampling Protocol: APU PM Emissions Measurements

APU PM emissions measurements were made on aircraft-mounted, in-service APUs during non-revenue generating periods, for example, when the aircraft was in the hangar for routine maintenance or was parked at an airport gate.

A measurement test matrix was developed to ensure the acquisition of a common set of emissions characteristics as a function of APU type and APU operating condition for each APU studied. Each APU was tested at three operational power settings: idle (no load), both packs (environmental control condition), and motoring engine (main engine start). Each APU's operating condition was defined by revolutions per minute (RPM) and exhaust gas temperature (EGT) settings. The meteorological conditions under which each test was conducted were also recorded. The emissions characteristics measured included total and non-volatile PM mass- and number-based emissions indices (EIs), number-based geometric mean diameter, and geometric standard deviations, PM-bound organic fractions, and CO_2 concentrations. The full complement of measurements per APU operating condition was acquired within a 5-minute period once the APU was deemed stable at a given operating condition. Fuel samples from each APU were acquired (where possible) and analyzed off site for the following fuel properties: carbon content, hydrogen content, aromatic content, and sulfur content.

2.2.2 Sampling System

The mobile laboratory shown in Figure 6 is a 24-foot box truck with an advanced sampling system incorporated into it. The mobile laboratory has a diaphragm pump as well as a scroll pump to entrain the sample for all the instruments. During the measurements, a tow generator was used to provide power to the mobile laboratory for both the ARI and Missouri S&T equipment as well as for air conditioning. In addition to the instrument suite inside, the mobile laboratory also recorded ambient wind speed, direction, and continuous GPS data.

2.2.3 Probe Design: APU Emissions

Emissions samples were extracted through an adjustable height probe, as illustrated in Figure 7, placed 1 m to 5 m behind

Figure 6. Aerodyne mobile laboratory.

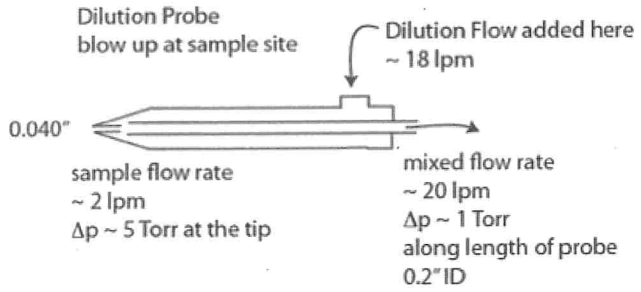


Figure 7. Illustration of APU emissions sampling probe.

the APU exhaust port. The probe was connected by a flexible line to the inlet port on the mobile laboratory. The height of the probe was adjusted for each APU (depending on its height above ground) such that the probe was in the core exhaust flow of the APU exhaust stream. The PM sampling probe was designed to provide probe tip dilution, thereby reducing or eliminating sample modification as a function of the sample extraction process, and to keep the mixing ratios within a calibration regime suited to both ambient and levels elevated due to combustion. Figures 8 through 10 show the sampling system employed to sample PM emissions from APU mounted on several different airframes. The APU exhaust stream does not have any appreciable thrust, and, as a consequence, was influenced by the ambient wind, which further diluted the sample.

2.2.4 Probe Design: Tire and Brake Emissions

The mobile laboratory had two ports that sampled emissions in real time. One port provided samples to instruments measuring PM number concentration, black carbon (BC) mass, PM size distribution, and mass-based composition information. The other port provided samples to the instruments measuring gas phase species such as carbon monoxide (CO), nitrogen oxide (NO), nitrogen dioxide (NO_2), ethylene (C_2H_4), formaldehyde (HCHO), acetaldehyde, benzene, and propene. Carbon dioxide (CO_2) was measured on both inlets using three different instruments.

Figure 8. Aerodyne mobile laboratory positioned behind a B767 aircraft to measure PM emissions from the GTCP 331-200 APU.

Figure 9. Measuring PM emissions from a GTCP 331-500 APU on a B777.

2.2.5 Instrumentation Suite

All instruments were housed in the mobile laboratory to facilitate ease of movement around the airport complex. The PM and gas phase instrumentation suite used to measure emis-

Figure 10. PM sampling probe behind an A320 aircraft with GTCP 36-300 APU.

sions from APUs, tires, and brakes during both the winter and summer studies are described in the following subsections. PM size, number, mass, and composition information was collected using the instrumentation suite described in Section 2.2.5.1. Gas phase data was also acquired during the study using the instrumentation suite described in Section 2.2.5.2. These gas phase measurements were primarily used to corroborate APU and main engine operating conditions at which PM data was acquired during emissions measurements of aircraft APUs, tires, and brakes.

2.2.5.1 PM Emissions Measurement Suite

2.2.5.1.1 PM Number. Particle number concentration was determined using both TSI Model 3775 and TSI Model 3022 condensation particle counters. Saturated butanol vapor is used to grow submicron particles to sizes where they can be optically counted. The specifications describe a 50% response cutoff for ~4 nm, and the instruments essentially do not count particles below this size threshold. The 3022 Model CPC was also run downstream of a 2.5 μm cyclone limiting the size of particles to those under 2.5 μm.

2.2.5.1.2 PM Mass. BC PM mass was measured using a thermo electron multi-angle absorption photometer (MAAP) (Petzold and Schonlinner 2004, Petzold et al. 2005). The MAAP measures particulate BC by collecting aerosol onto a 2 cm^2 quartz fiber filter tape. The transmission and scattering of 630 nm wavelength light-emitting diode (LED) light are monitored by multiple photodetectors. A two-stream radiative transfer calculation separates the scattering from the absorption component for the total particle loading on the filter tape. The instantaneous loading is computed by the derivative of the total.

PM mass was also measured using a Cavity Attenuated Phase Shift (CAPS)-based particle extinction monitor (PMex) (Aerodyne Research) which employs an LED centered at 630 nm. The CAPS PMex monitor supplies its own purge air, which prevents particles from fouling the mirrors. Both pressure and temperature of the gas within the cell are measured and used to subtract the contribution to the total extinction from gas phase Rayleigh scattering (Yu et al. 2011).

2.2.5.1.3 PM Size. A Cambustion DMS500, a state-of-the-art fast particulate spectrometer, was used to gather real–time size distribution information and total concentration of engine exhaust PM. The DMS500 has a fast size distribution measurement rate (up to 10 Hz) (Reavell et al. 2002), which permits sampling of plumes in a dynamic environment. In this instrument, the PM sample is passed through a cyclone separator to remove particles larger than 1 μm and electrically charged with a corona charger, and then introduced into a strong electrical field established in a classifying column. The field forces the charged particles to drift toward an array of electrometers through a sheathing gas flow created in the column. The location at which a charged particle reaches the electrometer array depends on its aerodynamic drag/charge ratio. Real-time monitoring of the electrometer outputs provided a measure of the particle size distribution. The DMS500 has demonstrated good agreement with traditional, slower sizing instruments under field conditions (Hagen et al. 2009) and has been has been previously used to sample gas turbine engine exhaust in the near field (Lobo et al. 2007a, Lobo et al. 2007b) and in evolving plumes (Herndon et al. 2008, Lobo et al. 2012).

A TSI Optical Particle Sizer (OPS) Model 3330 was used to provide fast measurement of PM concentration and PM size distribution in the size range 0.3 to 10 μm using single particle counting technology. In the OPS, the PM sample enters an optical chamber where it crosses a laser beam, creating a light pulse. The light pulse intensity is used to count and size the particles, yielding a PM size distribution.

2.2.5.1.4 PM Composition. Mass-based composition data was measured using an Aerodyne Soot Particle-Aerosol Mass Spectrometer (SP-AMS) instrument, a standard Aerodyne high resolution time-of-flight aerosol mass spectrometer (HR-TOFMS) with an intracavity, continuous wave (CW) laser vaporizer (Onasch et al. 2012). The SP-AMS was operated to provide online chemically speciated mass and sizing measurements of both non-refractory and refractory particles between roughly 50 nm and 600 nm in aerodynamic diameter. Details pertaining to the SP-AMS are presented in Onasch et al. 2012. In the SP-AMS, particles containing refractory materials (e.g., BC and many metals) are vaporized with a 1064 nm laser. The resulting vapor is ionized via electron impact and detected with the HR-TOFMS. A heated tungsten surface (600°C) that is typically used in traditional Aerodyne AMS instruments (Jayne et al. 2000, Canagaratna et al. 2007) was also used to measure the composition of any non-refractory particles. A consequence of this vaporizer set up is that the species measured at any point in time are a combination of species vaporized with the conventional heater and species vaporized with the 1064 nm laser. PM measurements were conducted at 1-second time resolution during plume measurements on the taxiways.

2.2.5.2 Gaseous Emissions Measurement Suite

CO_2 was determined primarily using two Licor-6262 non-dispersive infrared absorption instruments. A Licor-820 was used as a redundant measurement of CO_2 on the second inlet. The in-field calibration of the CO_2 instruments was accomplished using a 400 parts per million by volume (ppmv) standard

and "CO_2-free" zero air. The time response of each of the Licor instruments was flow rate limited. The 1/e time response was determined to be less than 0.9 seconds for the CO_2 instrument on the gas phase inlet and 1.1 seconds for the pair of CO_2 instruments on the second inlet.

NO_2, CO, and HCHO were measured using tunable infrared differential absorption spectroscopy (TILDAS) using pulsed quantum cascade lasers (Jimenez et al. 2005). The NO_2 absorption feature, at 1606.37 cm^{-1} has been used in previous measurement campaigns (Shorter et al. 2005). CO was monitored using the infrared absorption line at 2183.2 cm^{-1}. HCHO and formic acid (HCOOH) were measured at 1765 cm^{-1}. The inlet characterization and calibration system for HCHO used during this campaign was described in Subsection 2.2.3 (Herndon et al. 2007). NO was measured using a Thermo 42i chemiluminescence analyzer.

A Proton Transfer Reaction Mass Spectrometer (PTR-MS) (Knighton et al. 2007) was deployed to monitor a wide variety of potential hydrocarbon (HC) emissions. Interestingly, no HC emissions were measured that correlated with tire emissions events. In particular, the peaks associated with benzothiazole were tracked explicitly, due to its use in tire production and the observation of a benzothiazole species in the AMS signal. Any relevant benzothiazole emissions were below the detection threshold of the PTR-MS, indicating that the AMS-measured phenylbenzothiazole was essentially all in the condensed phase particles by the measurement point.

2.3 Calculation of APU EIs

Non-dispersive infrared absorption instruments were used to measure the gas phase CO_2 concentration in the sampled plume. The gas phase CO_2 concentration is used to relate the measured PM number and mass concentration to fuel-based PM number- and mass-based EIs, EIn and EIm, respectively, with units of number of particles per kilogram of fuel burned (number/kg fuel) for number concentrations and milligrams of PM per kilogram of fuel burned (mg/kg fuel) for mass concentrations. For a given exhaust component concentration, X, the EI(X) is calculated using equation 1:

$$EI(X) = (\Delta X/\Delta CO_2) \times EI(CO_2) \times M_{air}/M_{CO_2} \times (1/\rho_{air}) \quad \text{(Eq. 1)}$$

where $\Delta X/\Delta CO_2$ is the emissions ratio for the exhaust component, M_{air} is the molar mass of air, M_{CO_2} is the molar mass of CO_2, and ρ_{air} is the density of air at ambient conditions. This expression is based on 100% conversion of the carbon in the fuel to CO_2. Corrections for incomplete combustion can be made, based on measurements of CO and HC emissions, but these corrections are within experimental uncertainties for the measurements reported here. EI (CO_2) equals 3160 g CO_2/kg fuel (based on the H/C composition of the fuel, see Table 4) for most available Jet A fuel, within a few percent. EIs are also calculated for PM number concentrations (number/kg fuel) in a similar manner.

2.3.1 APU PM Emissions Measurements

PM emissions from in-service commercial APUs from the fleet of UAL were measured on March 8, 2011. The first round of testing occurred near the maintenance hangar of UAL, and the second round was conducted in the terminal area where the aircraft were parked at the gate. Overall, emissions data from three different APU model types was acquired on four different airframes. Table 3 lists the details of the APU emissions measurement activity.

PM emissions data during the first round of testing was acquired at three APU operational states—idle (no load), both packs (environmental control condition), and motoring engine (main engine start). Fuel samples were collected from each aircraft during this round of measurements. During measurements in the terminal area, data was acquired at the idle and both packs operational states. It was not feasible to run the motoring engine condition or to acquire fuel samples in the terminal area. During the APU emissions measurements, APU

Table 3. Summary of APU emissions measurements.

Test Number	Date	Test Start Time	Test Stop Time	Measurement Location	Airframe	APU Model
1	3/8/11	12:24:00	12:52:00	Outside Hanger	B767-200	GTCP 331-200
2	3/8/11	14:34:00	15:03:00	Outside Hanger	B777-200	GTCP 331-500
3	3/8/11	16:32:00	16:52:00	Outside Hanger	A320	GTCP 36-300
4	3/8/11	22:28:00	22:43:00	Terminal	A320	GTCP 36-300
5	3/8/11	22:56:00	23:09:00	Terminal	A320	GTCP 36-300
6	3/8/11	23:35:00	23:50:00	Terminal	A319	GTCP 36-300

Table 4. Results of fuel analyses.

Test Number	Density @15°C (kg/L)	Carbon content (% mass)	Hydrogen content (% mass)	Sulfur content (ppm)	Aromatic content (% vol)
1	0.801	86.2	13.8	479	17.5
2	0.801	86.2	13.8	189	18.8
3	0.807	86.4	13.6	238	21.1

operating condition along with RPM and EGT were recorded for each model type studied.

The acquired fuel samples were analyzed for carbon-hydrogen content, fuel aromatic content, and fuel sulfur content. The results of the fuel analyses are presented in Table 4. The results of the analysis indicate that the chemical composition of fuels used in this study is consistent with those currently being used in the commercial fleet.

Fuel analyses data provided by Matt Dewitt and Edwin Corporan, United States Air Force.

2.4 APU PM Observations

For the GTCP 331-200 and GTCP 331-500 models, only one APU was studied for each model and the data presented represents the average value over a time period corresponding to a stable operating condition. For the GCTP 36-300 model, four APUs were studied and the data presented in the following subsections represents the average value for these measurements over all APUs for a specific operating condition.

2.4.1 Size Distributions

PM emissions samples were diluted by ambient air in addition to dilution at the probe tip with nitrogen. While the dilution as a result of mixing with ambient air is not explicitly quantified, the PM size distributions are presented as differential, number-based EIs (dEIn/dlogDp), where the simultaneously measured CO_2 concentration is used to account for the overall dilution factor (probe tip + ambient dilution) and to normalize the data to fuel flow rate (see Section 2.3). This approach for normalizing the PM concentration data in expanding plumes has been used in previous PM emissions measurement campaigns (Lobo et al. 2007a, Herndon et al. 2008, Lobo et al. 2012). PM emissions size distributions data was acquired as a function of the three APU operating conditions: idle, both packs, and motor engine, for each APU model studied. Figures 11, 12, and 13 present the average EIn size distributions measured at the exit plane as a function of APU model for the idle, both packs, and motor engine conditions, respectively.

For a given APU operating condition, the size distribution is found to vary across the three different APU models studied in terms of shape and number. Differences in the size distributions are also observed between different operating conditions for the same APU model. These differences are summarized in Table 5.

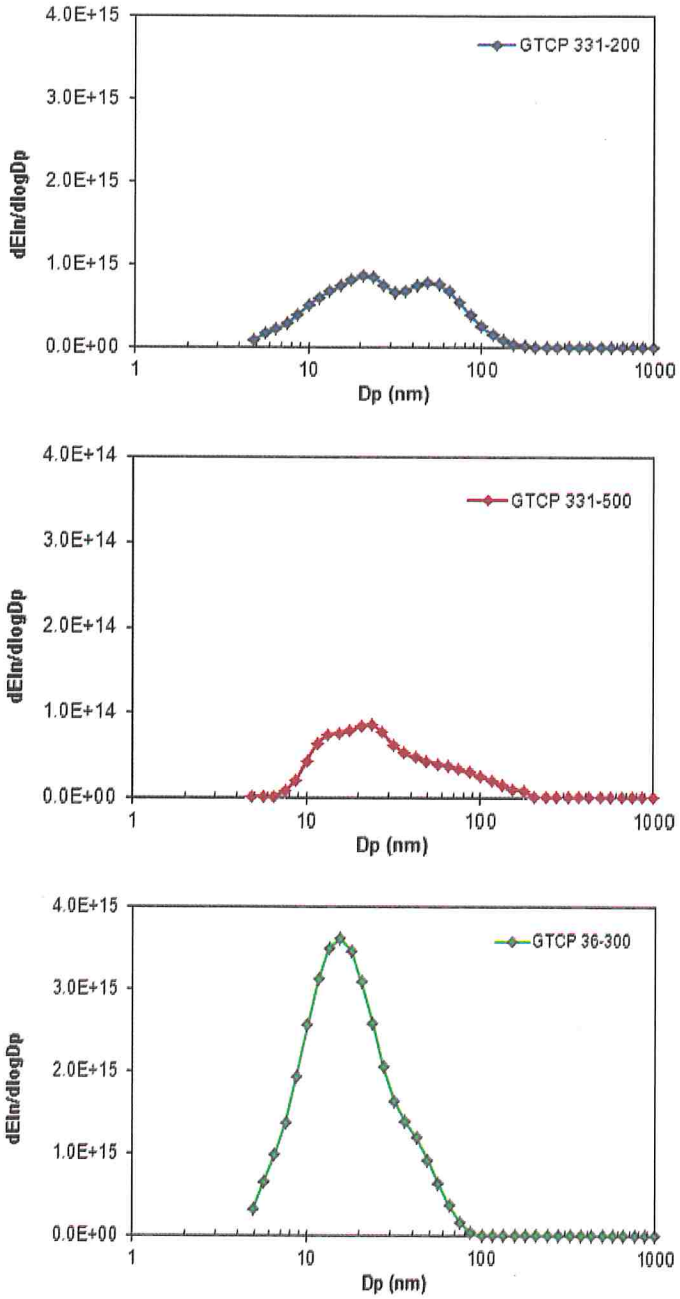


Figure 11. PM EI size distributions for GTCP 331-200, GTCP 331-500, and GTCP 36-300 APU models operating in the idle mode.

2.4.2 Number-Based EI

The number-based EI for the APU models studied as a function of operating condition is presented in Figure 14 and summarized in Table 5.

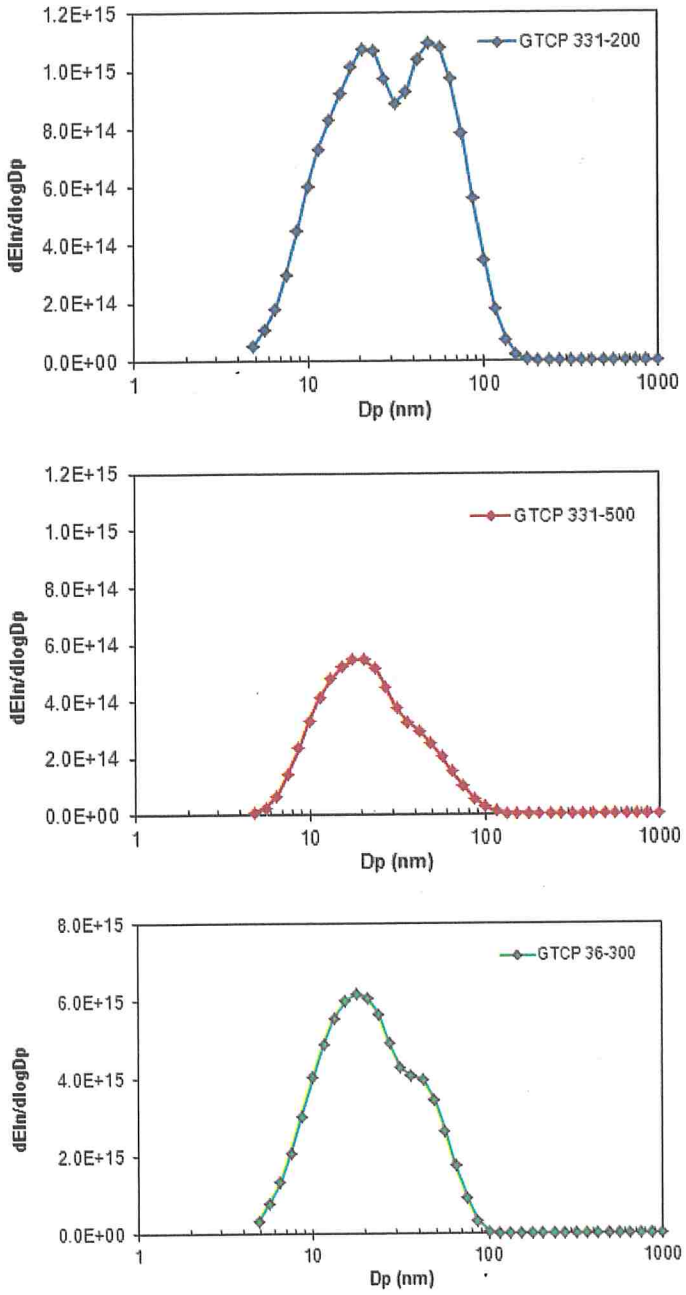


Figure 12. PM EI size distributions for GTCP 331-200, GTCP 331-500, and GTCP 36-300 APU models operating in the both packs mode.

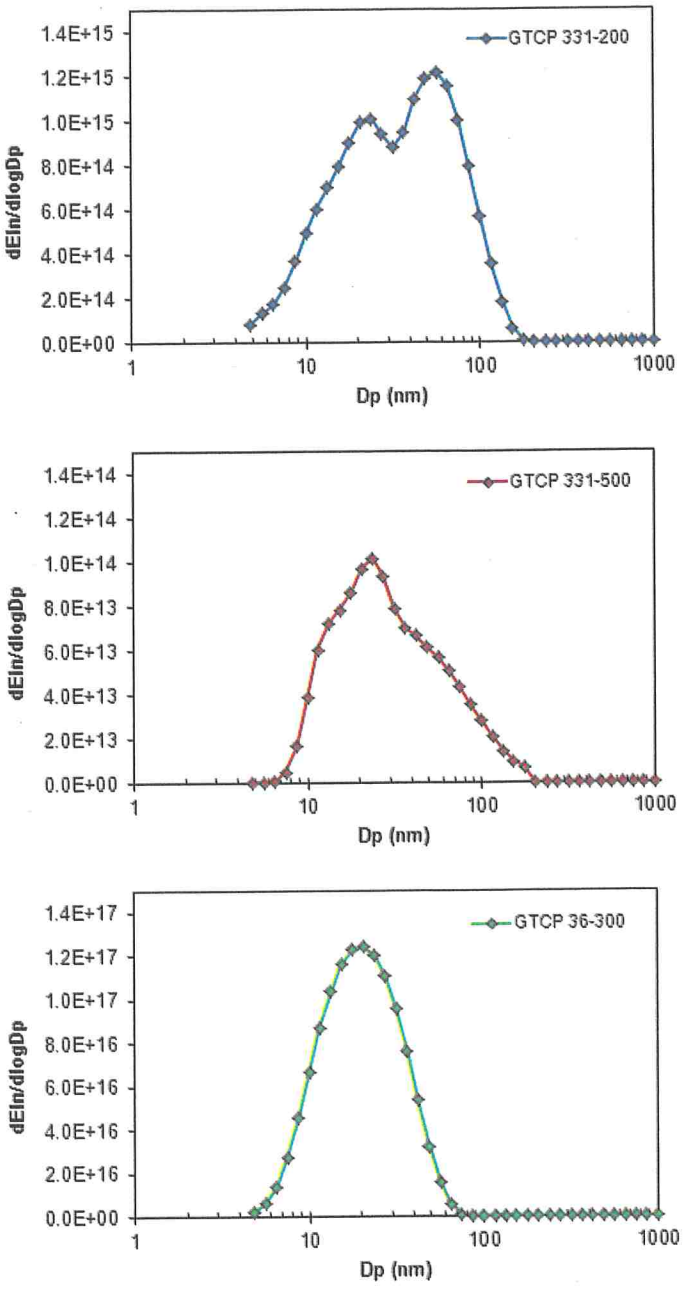


Figure 13. PM EI size distributions for GTCP 331-200, GTCP 331-500, and GTCP 36-300 APU models operating in the motor engine mode.

Table 5. Summary of APU PM emissions for each APU model studied as a function of operating condition.

APU Model	*Operating Condition*	*GMD (nm)*	*GSD*	*EIn (#/kg fuel)*	*BC EI (mg/kg fuel)*
GTCP 331-200	Idle	30 ± 4	2.2 ± 0.1	$(8.0 \pm 7.4)\times10^{14}$	112 ± 23
	Both Packs	29 ± 2	2.1 ± 0.1	$(1.0 \pm 0.3)\times10^{15}$	103 ± 35
	Motor Engine	33 ± 2	2.1 ± 0.1	$(1.0 \pm 0.3)\times10^{15}$	196 ± 53
GTCP 331-500	Idle	30 ± 3	2.1 ± 0.0	$(6.4 \pm 2.1)\times10^{13}$	20 ± 1
	Both Packs	22 ± 1	1.9 ± 0.0	$(3.8 \pm 1.4)\times10^{14}$	21 ± 2
	Motor Engine	31 ± 3	2.0 ± 0.1	$(7.5 \pm 3.0)\times10^{13}$	11 ± 2
GTCP 36-300	Idle	17 ± 2	1.8 ± 0.1	$(2.3 \pm 1.0)\times10^{15}$	39 ± 17
	Both Packs	20 ± 1	1.9 ± 0.1	$(4.5 \pm 0.9)\times10^{15}$	104 ± 46
	Motor Engine	19 ± 2	1.7 ± 0.1	$(7.7 \pm 1.4)\times10^{15}$	425 ± 22

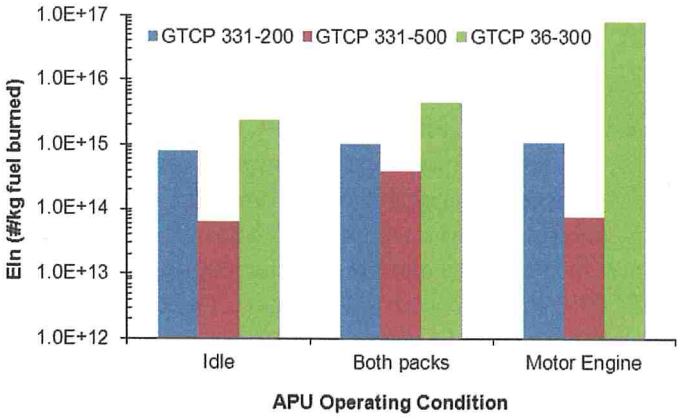


Figure 14. PM number-based EI for different APU models as a function of operating condition.

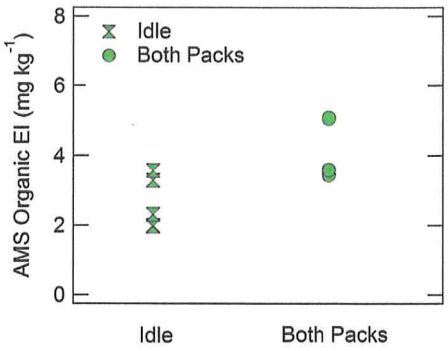


Figure 16. PM organic mass-based EI for the GTCP 36-300 APU measured during idle and both packs operating conditions.

2.4.3 BC Mass-Based EI

The BC mass-based EI for the APU models studied as a function of operating condition is presented in Figure 15 and summarized in Table 5.

2.4.4 Organic Mass EI

Figure 16 presents the organic mass-based EI data for the GTCP 36-300 APU model at the idle and both packs operating conditions. Data for the motor engine condition is not presented because there were large variations in the AMS signal at this condition. The primary operational mode of the APUs is with pack operating for normal usage at airports. Under this primary condition, APUs are typically operated for periods upwards of 20 minutes per aircraft turnaround. In comparison, the motoring power condition is only used during engine start procedures for extremely short durations. Thus, the motoring condition would not be expected to contribute significantly to the overall emissions of organics. While other emissions characteristics at the engine motor condition were reliable (mass and number), the variability in the organic contribution may be due to real variability in the (modest) amount of organic contribution to the PM during the short duration of the motoring tests.

2.4.5 Summary of Findings on APUs

In the winter 2011 study, PM emissions characterization for three APU types currently employed in the U.S. domestic commercial fleet were performed. The Emissions and Dispersion Modeling System (EDMS) database suggests that these APU types are found in a wide range of airframes, including narrow body and wide body jets. The research team estimates that these APUs conservatively represent 30% to 40% of all the APUs currently in use in the domestic fleet. This estimate is based on market share of the airframes in which they are installed, and weighted according to the airframe's operations at both hub and non-hub airports. The size distribution

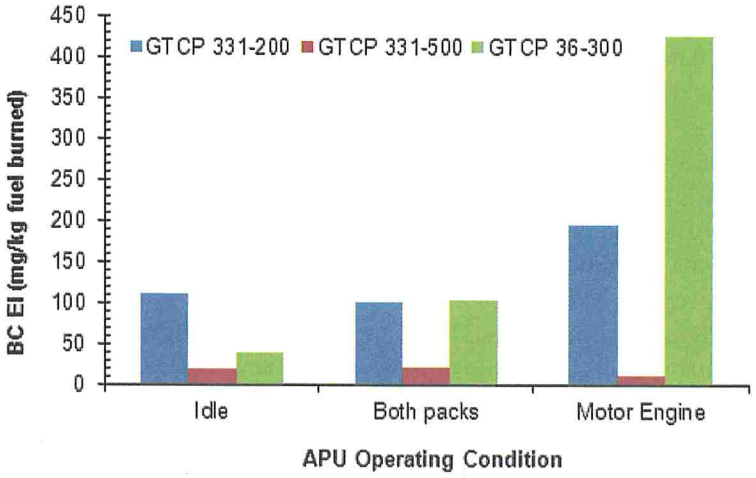


Figure 15. PM BC mass-based EI for different APU models as a function of operating condition.

parameters—geometric mean diameter (GMD) and geometric standard deviation (GSD), number and mass characteristics of the APU's studied are summarized in Table 5. These averaged parameters provide useful data for predicting the APU component of the aircraft-generated PM associated with aircraft activities at an airport.

From Table 5, it is clear that the GTCP331-500 APU, the more modern technology APU, has the lowest number and mass-based EIs among the three APU technologies investigated during the winter study. The data is the first of its kind for different APU models and reveals significant differences when compared with the emissions reported for the GTCP85-98CK APU studied in the AAFEX-1 campaign (Kinsey et al. 2012). The PM mass-based EI values for the GTCP85 APU were in the range of 200 mg/kg to 600 mg/kg fuel burned, compared with a range of 10 mg/kg to 425 mg/kg fuel for this study. For PM number-based EI, the range of values for the GTCP85 APU was 2 to 6×10^{15} particles/kg fuel compared with 6×10^{13} to 7×10^{15} for this study.

The APU data from this study also allows a comparison with main engine EI data. In *ACRP Report 9* (Whitefield et al. 2008) main engine emissions for a wide range of aircraft have been summarized. Number-based EIs for main engines range from 0.1 to 10×10^{15} particles/kg fuel and mass-based EIs range from 40 mg/kg to 700 mg/kg fuel.

It is worth noting that the exhaust is already diluted for these measurements, so these APU tests are more comparable to the "30-m" main engine test performed during the APEX and AAFEX series of studies than they are to the "1-m" main engine test during those studies. If the present APU organic results are compared with a variety of main engine 30-m data, the main engine data tends to vary between 0.5 mg/kg and 2 mg/kg fuel, with outliers like the RB211 up as high as 20 mg/kg to 30 mg/kg fuel. The organic PM loadings are broadly consistent with the range of observed EIs from main engine emissions. One complicating factor in making such a comparison, however, is that some types of main engine emissions have engine oil emissions (Yu et al. 2012). A more complete dataset of APU organic EIs would be needed to resolve genuine differences in the effective organic PM EI.

As with other APU emissions, the AMS organic contribution is quantitatively similar on an EI basis to the PM EIs for aircraft main engines. In determining APU overall contributions to airport PM emissions inventories, the fuel flow and operation times will need to be considered for realistic APU usage scenarios, which will vary greatly among different airport types. However, these EIs are an important first step in determining the potential for APUs to contribute to the PM emissions inventory and are an important benchmark for ongoing aircraft emissions impact analysis. It is also important to note that the data shows that APU PM EIs measured for older APU models such as the GTCP85 are not representative of APUs in the commercial fleet, and that the present numbers, which on an EI basis are similar to BC, CO or less than nitrogen oxides (NO_x) EIs for aircraft main engines. Thus, especially for BC, fuel burned generates similar BC whether in an APU or a main engine. This will be helpful for airport emissions inventory analysis.

PM emissions characterization from APUs was only performed during the winter study in order to get a more robust dataset for PM brake and tire emissions during the summer study. APU PM emissions reported are presented in terms of EIs, where the number or mass of PM is normalized to the amount of fuel burned. Thus, the APU emissions burden can be calculated by the time in an operating mode and the fuel flow rate associated with that condition. The PM EIs derived from this work can be considered a conservative (upper bound) level for annual PM EIs, since these winter-based EIs are expected to be higher in the winter months than in the summer months because emissions are usually higher in colder temperatures (*ACRP Report 63*, Herndon et al. 2012).

2.5 Tire and Brake PM Emissions Measurements

The PM emissions sample measurements from aircraft tires and brakes taken during routine operation in this study are the first of their kind. The sampling approach for measuring the tire and brake PM emissions used the same general approach that has been used to measure engine emissions for real-world aircraft operations at airports (Herndon et al. 2008, Lobo et al. 2012). To optimize the encounter with the tire/brake emissions plume, the sampling point was chosen to coincide with the locations downwind of the runway where most aircraft touch down (for tire PM) or apply the brakes. These were different and distinct locations on the runway, and the locations varied from landing to landing, so a central position was chosen to account for this variation.

2.5.1 Tire and Brake Emissions (Advected Plume)

Two sample inlets were employed on the front of the mobile laboratory. PM instrumentation and gas phase instrumentation were split between two inlets approximately 1.5 m apart and 2 m above the ground level. A common zero overflow was used to zero the instrumentation suite as well as to provide a means of time synching the two inlets. With the assistance of airport operations staff, the mobile laboratory was positioned close to active runways. This enabled real-time PM emissions measurements of aircraft activity—takeoff, landing, and braking—to be made in a real-world operations setting. Figure 17 shows the mobile laboratory positioned on a taxiway adjacent to the active runway to measure PM emissions of aircraft landing.

Figure 17. Mobile laboratory during PM tire and brake emissions measurements.

2.5.2 Tire PM Emissions Measurements

To unambiguously quantify the in-use tire "touchdown" emissions characteristics, two elements were required: (1) the instrumentation had to have a fast measurement rate with near 1-second response time and (2) the mobile laboratory had to be located as close as possible on the downwind side of the runway being used for aircraft landing. Additionally, the instrumentation needed to be able to distinguish the engine emissions from the combined tire/touchdown and engine/"approach" plume. The airport operations escort staff was generally able to secure permission from the terminal area air traffic controllers to position the mobile laboratory in the proper location. An example of such positioning was shown in Section 2 (Figures 3 and 5). It is also worth noting that not all touchdown events were "upwind." The touchdown event is not entirely predictable, that is, a landing could be short or long along the runway. During the testing campaign, conditions reflected good visibility, even during the rainy days, and pilots were able to touchdown near the middle of the "zone" predicted by airport operations escorts. As a result of the level of access and participation airport operations lent to the project, it was not difficult to position the mobile laboratory "downwind" of touchdown plumes.

The tire PM emissions measurements were taken at two sample ports located on the front of the mobile laboratory. The general orientation of the vehicle during the touchdown/tire measurement period was into the incident wind. During the data collection period, aircraft tail numbers were recorded, whenever visible, to ascertain airframe and engine information. The wind directions and speed were monitored in real time and activity taking place upwind was noted using time-stamped text entries. The aircraft activity was also recorded along the upwind vector using two webcams, which archived photos every second. In some cases, the mobile laboratory was quite close to the runway and with rapidly moving aircraft one of the webcam images (but not both) did not fully capture the body of the airframe. Based on the wind speed and GPS-based distance estimates, plume arrival times were computed and corroborated with the real-time CO_2 measurement of aircraft activity occurring on the runway, and the movements on the adjacent upwind taxiway. This approach led to the determination of the type of aircraft activity being observed, that is, "upwind," "taxi," "takeoff," or "touchdown" during landing.

Figure 18 presents a B737 aircraft landing with a puff of tire smoke as the wheels hit the ground. The photo was taken during the efforts to characterize brake emissions properties. As can be seen in the figure, the wind is conveying the touchdown plume from north to south (left to right in the photo reference). Were the mobile laboratory being used to characterize this touchdown event, it would be visible in the photo to the right, approximately as distant as the aircraft, as opposed to being positioned for measuring brakes, as is the case for this photo. Not all aircraft landings generated a discernible puff of smoke. Figure 19 presents a MD-80 landing with no visible tire smoke. This image was collected by one of the two webcam devices recording a time-stamped photo each second out of the front of the mobile laboratory.

The PM instrumentation suite used to measure tire and brake emissions was the same as that used to measure APU emissions. It was presumed that the particle size distribution might be larger than that of the engine BC soot emissions. A TSI OPS was added to the instrument manifest to measure PM size distributions in the 0.3 μm to 10 μm size range. A CAPS-based PM optical extinction monitor was also added which can be used to measure PM mass when the absorption properties are understood. Since extinction will, in general, need to be corrected for scattering before converting to mass, it is important to know the relative scattering to absorption contributions to extinction for a mass determination.

Figure 18. Aircraft landing at Chicago O'Hare International Airport with a puff of tire smoke.

Figure 19. MD-80 aircraft landing with no visible tire smoke.

2.5.2.1 Tire PM Observations

During the measurement campaigns, the wind direction and atmospheric conditions were variable. Despite changes in the wind direction, the advection field generally resulted in three essential types of perturbations to the background concentrations in the upwind fetch: terminal area emissions, takeoff plumes, and touchdown/approach plumes. The team notes that the typical engine state in the terminal area is near-idle, the takeoff is close to the maximum thrust setting, and the touchdown can be variable depending on the dynamics of executing a proper landing. The International Civil Aviation Organization (ICAO) databank contains tabulations of the EIs for NO_x and CO (ICAO, Aircraft Engine Emissions Databank, http://easa.europa.eu/environment/edb/aircraft-engine-emissions.php, 2012). The EIs are very different for these engine states and, as a result, plume origin can be robustly determined using NO_x/CO_2 and CO/CO_2 emissions ratios in the observed transient perturbations (or plumes).

2.5.2.1.1 Terminal Area Emissions. The distance between the mobile laboratory and the terminal and further taxiway areas was 500 m to 700 m depending on the incident wind vector. As a result, at the wind speeds encountered during this measurement period, these upwind emissions had been diluted and mixed horizontally, and vertically, resulting in broad plumes and slowly varying mixing ratios, compared with less diluted and more temporally peaked takeoff and landing events at distances within 100 m.

2.5.2.1.2 Takeoff Emissions. The distance from the mobile laboratory to the takeoff (and touchdown runway) was 63 m to the runway centerline. When aircraft employed the runway directly in front of the mobile laboratory, 13 to 24 seconds later, the instrumentation recorded increases in CO_2, NO and NO_2, and BC PM in relative ratios consistent with engine throttle states between 83% and 95% of thrust. The characteristic plume onset times are qualitatively sharper than emissions activity attributed to the terminal and taxiway vectors.

2.5.2.1.3 Touchdown Engine and Tire Emissions. The distance to the touchdown runway was the same as for the takeoff activity described. Visually, the emissions from the touchdown moment produced a pale blue-white aerosol puff that was generally violently deformed and mixed (presumably by the aircraft wake turbulence) and then carried in the prevailing wind where it visually faded (presumably due to dilution or microphysical processing). The CO_2 associated emissions of CO and NO_x were typically consistent with an engine throttle setting between 7% and 30%. The PM instruments employed were chosen to characterize the non-combustion emissions source as a result of the touchdown phenomenon.

The terminal area, taxiway, and takeoff engine emissions were not the focus of the project; however, preliminary analysis has been performed following the methodologies used in prior work. This analysis has been carried out whenever possible for diagnostic purposes to verify that the team's understanding of tire emissions is not affected by other emissions associated with engine operation, which have already been measured extensively in other tests.

2.5.2.2 Tire/Touchdown Emissions Capture and Quantification

During the six tire PM emissions testing periods, more than 70 touchdown emissions events were captured. The quantification of one touchdown event (March 10, 2011, 09:47:15), where both tire and engine emissions were detected, is presented in detail as an example.

The first important observation is that the character of the PM associated with the landing events was significantly different than those attributed to engine emissions. The touchdown PM signature was unique when viewed using the ensemble of PM characterization methods and is distinctly different from engine or APU emissions. In Table 6, a simplified synthesis of

Table 6. Proximate emissions signature matrix.

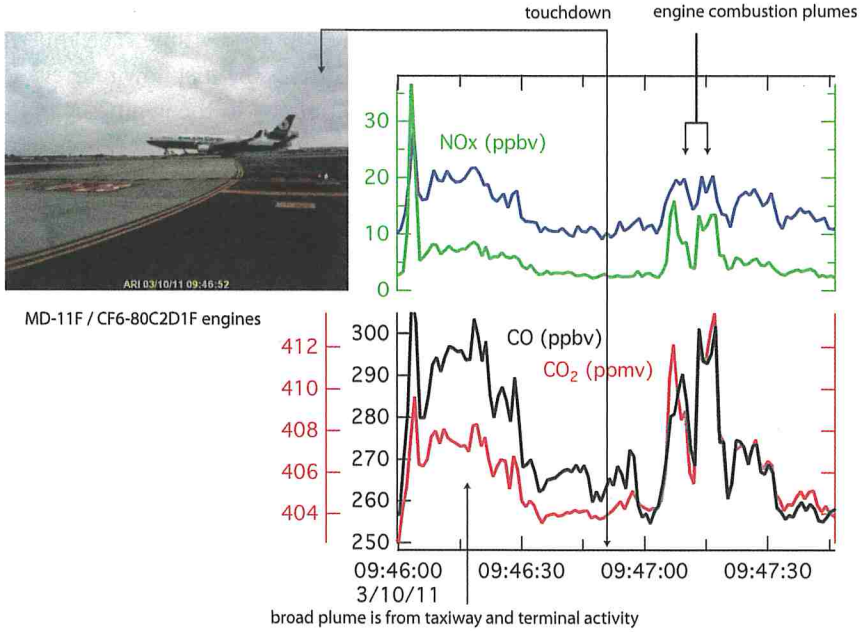
	AMS mz=211	*OPS*	*MAAP*	*CAPSex (L.A.A)*	*CO_2*
Tire	Yes	Yes	No	Yes	No
Engine (Approach)	No	No	Yes	Yes	Yes
Engine (Takeoff)	No	No	Yes	Yes	Yes

the measurement matrix is tabulated based on the apparent response of the various instruments. The table should not be interpreted as having relevance to the total emissions burden described by the analytical vector, but rather as a qualitative understanding that is consistent for all the plumes characterized in this study. The table has columns for each of the instruments that proved most useful in analyzing the tire emissions, excluding the NO_x and CO data used to estimate the engine state. The rows of the table list the types of events that were observed, including the tire events of interest as well as engine emissions events from both takeoff and landing situations. Note that this table is based on cases in which the tire emissions are totally distinct from engine emissions but, even when the tire and engine emissions are commingled, the relative contributions from tires and engines can be determined based on their distinct emissions signature. In quite a few cases, the tire emissions are entrained in the source aircraft trailing vortex system and are mixed with the engine emissions.

Table 6 indicates which instruments responded to the different events and focuses on what distinguishes the tire events. Notably, the AMS (aerosol mass spectrometer) 211 signal (attributed to phenyl benzothiazole) and the OPS are only associated with tire events. Similarly the MAAP and CO_2 measurements are only associated with engine events. It can be seen in the table that the CAPS, which measures Light Absorbing Aerosol (L.A.A) and total scatter, responds for both tire and engine events. The rapid temporal response and sensitivity of the CAPS, however, makes it very useful for analyzing the tire signature. The combination of all these instruments can make the unambiguous identification of a tire event that can be analyzed for the associated emissions.

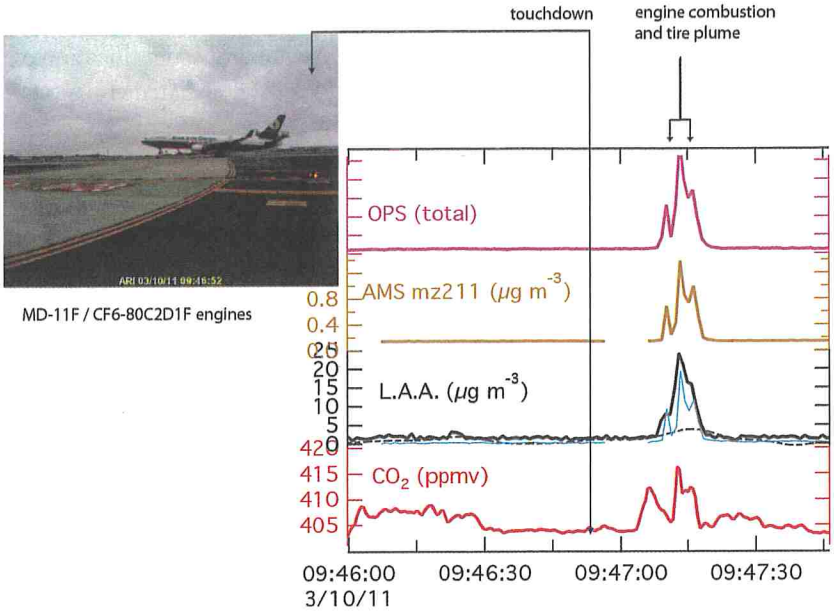
The gas phase emissions associated with the touchdown event for an MD-11 occurring March 10, 2011, 09:47:15 are presented as a time series in Figure 20. The CO and NO_x EIs for this event are consistent with an engine operational throttle level between the idle and approach engine states (specifically the engines are likely operating between 22% and 29% rated thrust as the aircraft passes into the virtual "upwind" sampling volume). The PM emissions associated with the 09:47 touchdown are presented as a time series in Figure 21.

The CO_2 time series in Figure 21 is similar to that shown in Figure 20, but not identical, because it was collected on a co-located sample port dedicated to PM measurements. The research team does assume that the two plumes in CO_2 depicted here correspond to the engine states determined by the gas phase traces presented in Figure 20. At this approach throttle setting, the engine-related PM emissions are anticipated to be modest, and this is supported by the gentle response of the MAAP measurement (black trace in Figure 21) and therefore the stronger enhancements in the OPS, AMS mz=211, CAPSex, and AMS BC proxy signal must be attributed to tire-related PM emissions. The AMS total BC proxy is an AMS signal based on laser ablation of the BC and is consistent with the MAAP BC trace. This signal is used as a quality-control, redundant measurement of BC when available, but is not discussed further in any detail in the subsequent analysis.



(The inset photo in the top left shows the time coded webcam image of the landing aircraft. The time series depicts the measurements of NO_2 (blue), NO (green), CO (black) and CO_2 (red) on the gas phase inlet.)

Figure 20. Gas phase sample time series for event 0947.



(The inset photo is of the associated touchdown event. From the top, the plots show the time series of the OPS total concentration (pink), the AMS mz=211 (amber), the CAPS extinction monitor of L.A.A. (dotted line), the AMS total BC proxy (light blue), the MAAP soot measurement (black), and the CO_2 (red).)

Figure 21. PM characterization of event 0947.

Two alternative methods have been used to estimate the total mass-based PM emissions for this touchdown. The first method is a volumetric-based approach calculated using equation 2:

$$\text{Total mass} = \text{Peak value}\ (\mu g/m^3) \times (\Delta t_p + \text{wind speed}/2)^3 \qquad \text{(Eq. 2)}$$

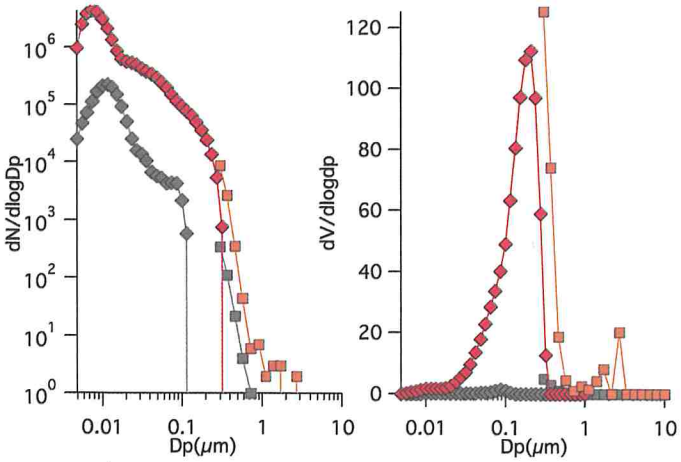
The peak value is the largest mass concentration value measured during the plume intercept. In the 09:47 example, this peak value is 22 μg/m³. The Δt_p term refers to the duration of the plume intercept. The wind speed term scales the spatial extent of the plume. This method assumes a roughly spherical puff, with an overall concentration related to the peak signal measured.

The second method uses the associated CO_2 emissions rate and an estimate of the amount of time in the upwind sampling volume, using equation 3:

$$\text{Total mass} = \text{PM EI}\ (g/kg\ \text{fuel}) \times \text{Fuel Flow Rate}\ (kg/s) \times \Delta t_v\,(s) \qquad \text{(Eq. 3)}$$

This second method is based on assuming that the emissions are generated for a brief time while the tire is being rotationally accelerated from being at rest to rotating at the speed of the landing aircraft. The emissions are assumed to be entrained in the trailing vortex systems, just as the engine emissions have been entrained. This method is only applicable for such cases, when the trailing vortex system has mixed the tire emissions with those from the engine. The method, then, uses the concept of an EI, which is calculated based on the dilution of the emissions using CO_2 as a marker for the engine emissions and, for this method, tire emissions, as well. Thus, the tire emissions are treated on a similar basis as an engine emission, and an EI is calculated from the CAPS and CO_2 signals. Once an EI has been calculated, the total emissions are related to the emissions rate multiplied by time. The emissions rate is the product of the EI times the fuel flow rate; even though the tire emissions are unrelated to the engine operation, their mixing with the engine exhaust allows them to be treated in an equivalent manner. In this context, the total tire signal is the product of the CAPS PM EI, the fuel flow rate, and the emissions duration (tire spin up time for the tire event). For the 09:47 touchdown, these two methods for the CAPS-based quantification of PM, yield estimates of 285 mg and 250 mg per touchdown. An alternative quantification using the size distribution data presented in Figure 22 is described below.

The OPS/DMS volume size distribution measurements, shown in Figure 22 (right panel), can be integrated to produce units of PM volume per volume of sampled air. Through the use of a density assumption, a mass loading can be derived from the volume projection of the size distribution and can be compared with the extinction-based mass loading of the CAPS, which assumes an extinction-to-mass constant (extinction represents contributions from both absorption and scattering). For the curves in Figure 22, this integration with an assumed effective density of 1 g/cm³ leads to an estimated mass



(The left panel is the size distribution as measured by the instrument in dN/dlogDp vs. Dp while the right panel is the volume projection of these size distributions. The red and orange traces are the touchdown plume size distribution measurements of the DMS500 (red) and OPS (orange). The grey traces are from a period associated as "background").

Figure 22. Size distributions for background and touchdown associated plume as measured by the DMS500 and the OPS.

concentration of at least 8 μg/m³, which compares favorably with the estimate based on the CAPS peak value of 22 μg/m³.

2.5.2.2.1 Estimate of Tire PM Emissions Relative to Engine LTO PM Emissions. To put the CAPS-based quantification of tire PM emissions in context with the LTO-based estimated total PM emissions due to the operation of the aircraft main engines, the team considered some of the primary PM EIs that have been measured using modern BC characterization technologies. In general, the majority of the BC PM emissions result from the high fuel flow associated with takeoff and climb out. Taking characteristic numbers for takeoff and climb out, the EI for a single engine is ~100 mg of BC per kg fuel. At a fuel flow rate of 1 kg per second, two engines operating for the 174 seconds (0.7 + 2.2 minutes) stipulated for takeoff and climb out to 3,000 ft would constitute a total burden of primary BC PM 100 mg/kg * 1 kg/s * 2 engines * 174 s * 1 g/1000 mg = 34. This is a very cursory approximation designed to help bou and contextualize the estimate of 250 mg to 285 mg of tire emissions quantified for the 09:47 event. Thus, just consid ing the total mass of emissions, the contribution from tire <1% of the PM mass emitted during a characteristic takeoff climb out for the example considered here.

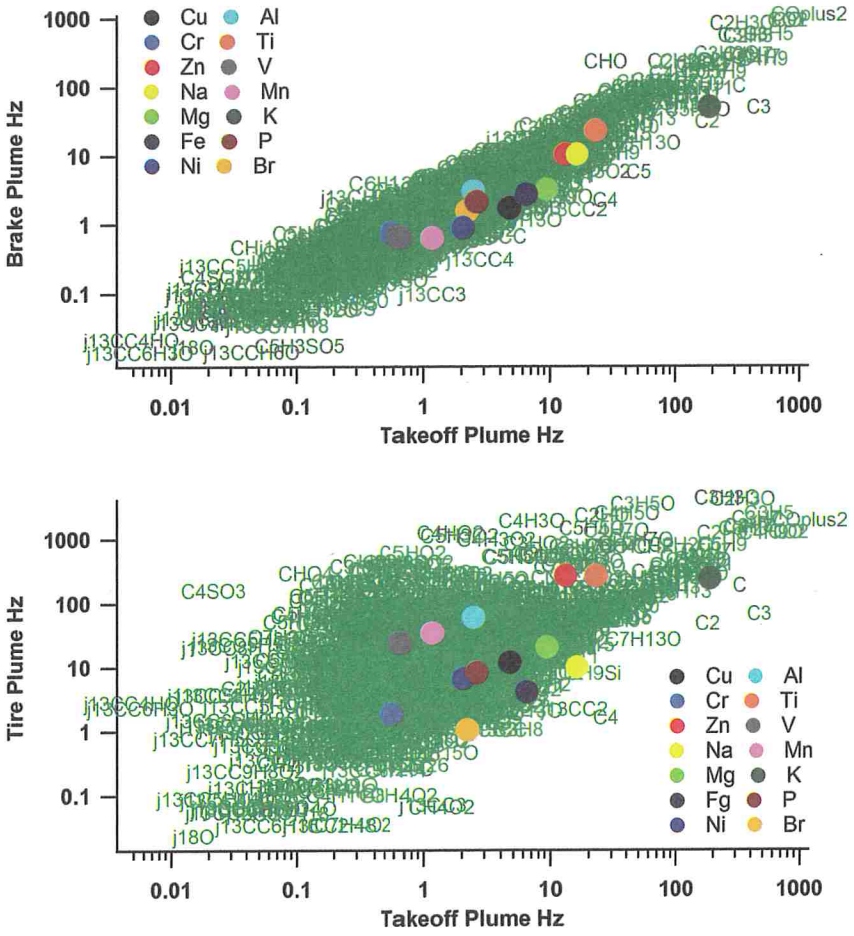
2.5.2.3 Summary of Findings on Tires

Touchdown events have been analyzed by the meth described in the previous subsections, accounting for varia ity in the touchdown emissions. From the team's experien the precise touchdown dynamics (which will depend on craft loading, weather conditions, and the pilot's response to entire situation) can strongly influence the resulting emissio and can be quite variable even for the same aircraft. Howe the total emissions have a range shifted to a larger maxim for larger aircraft, and a range centered on a smaller total emissions for smaller aircraft. So, while the MD-11 discus above resulted in estimates of 285 mg and 250 mg, the team obtained estimates for smaller aircraft of B757-222: 2 mg 71 mg; A320-232: 80 mg and 64 mg; B737-4B7: 43 mg and 2 and A320-232; 30 mg and 36 mg. In all cases, the first estim is based on the spherical puff estimate and the second is ba on the EI analysis. In a few cases, a very low estimate of a mg was obtained and probably indicates a shortcoming the analysis method for that particular case. For all cases, single-aisle aircraft have total PM emissions in the range 30 mg to 80 mg per landing, in contrast to the wide body e mate of 270 mg per landing. And, again, there is signific landing-to-landing variability even for the same aircraft ty

Representative subsets of the upper limit on the tire PM per touchdown event (total of all wheels) are tab lated in Tables 7 and 8. The estimates of the upper limit tire emissions to the atmospheric PM burden for the "d

Table 7. Selected winter *dry* touchdown measurements.

Plume Start Time	Airframe	Peak Particle Volume (μg/m³)	Approximate Plume Duration (s)	Plume Average Wind (m/s)	Tire Loss Upper Limit (mg)
3/10/11 09:47:10	MD11F	127	10	1.3	249
3/10/11 09:57:17	CRJ702ERNG	32	5	1.8	23
3/10/11 10:01:28	AE3007A1	28.7	8	2.5	230
3/10/11 10:04:31	737-832(W)	2.87	5	1.7	2
3/10/11 10:05:52	747-4KZF	123	9	1.75	481
3/10/11 10:08:51	ERJ170-200LR	72	6	2.36	204
3/10/11 10:23:09	AE3007	38	7	1.74	69
3/10/11 10:24:32	777-222ER	42.1	12	2.6	1279
3/10/11 10:26:40	757-222	16.2	5	1.9	14
3/10/11 10:33:24	A320-232	83	6	1.7	88
3/10/11 10:37:48	737-487	134	10	1.7	658
3/10/11 10:39:46	EMB145LR	19	4	2.1	11
3/10/11 10:42:49	A320-232	53	3	1.9	10



(The top graph depicts the intensities of organic chemical species as well as metal species measured with the SP-AMS for brake plumes relative to takeoff plumes while the bottom graph depicts these intensities for tire plumes relative to takeoff plumes.)

Figure 26. Organic chemical species measured by SP-AMS.

CHAPTER 3

Conclusions and Suggested Research

3.1 Conclusions

The PM EIs from several in-service APU engines were determined to be very similar to EIs for larger aircraft jet engines, which have been characterized extensively in prior studies. Relatively few APUs have had their emissions studied, and those that have represent a very limited set of data from older model APUs. Data from this project has confirmed that APU PM EIs from in-service engines are much lower than those reported in those prior studies. EIs, comparable to those used in advanced emissions models, were computed for three APU types, which are representative of the current technology most commonly found in the U.S. commercial airline fleet. The PM EIs were computed at the three operational power settings.

Measurements made near landing runways indicate PM emissions of particles smaller than 10 μm are from tire wear. Indeed, emissions measurements show that particles are emitted into the atmosphere when aircraft land. These are characterized by a puff of smoke associated with the tires contacting the runway. More than 100 aircraft landings were monitored, and measurements collected from 23 aircraft landings were used to characterize tire emissions. Estimates of the maximum amount of PM mass released during these landings suggest that less than 1% of total PM emitted during an LTO comes from the aircraft tires. Notably, little or no PM is emitted when aircraft land on a wet runway.

Several emissions plumes were sampled during the braking phase of landing aircraft. No distinct emissions signatures from aircraft brakes were discernable and it is infeasible to compute an EI for aircraft brakes. However, the data analyzed suggests that contribution of brake PM to overall PM inventory at this particular airport is negligible.

As a significant contribution to the current state of the art in airport emissions assessment, EIs were determined for APUs and tires. These indices can be incorporated into current emissions models used for airport air quality studies.

3.2 Suggested Research

Three types of emissions sources at airports were considered in this study. The research team offers recommendations for each type in turn.

3.2.1 APUs

Several representative APU engines were measured in the present study, which demonstrated that current in-service APU EIs are not significantly different from those of main engines. The EIs obtained can be used to characterize the fleet's APU operations, in combination with operational times-in-mode and fuel flow data. However, additional research could be conducted to include more APU manufacturers and models in a database that would provide APU emissions data for emissions inventory analysis.

Such a database could be structured similarly to the ICAO databank for main engines and could provide a similar service to the airport community.

3.2.2 Tires

The measurements performed in this study provided estimates for the emissions from tires that occur when the tires contact the runway pavement upon landing. These are estimated to be a small fraction of a typical LTO PM emissions from the main engines of the aircraft. Thus, if all PM is considered equally, the mass from the tires should be considered negligible. One avenue for future research could be to determine if there is anything particularly harmful in the tire emissions that should be of concern from a health perspective. As far as the tire emissions' number and mass is concerned, these results have shown very clearly that tire emissions are very small compared with engine emissions. So, unless there is something that is particularly toxic or in other ways harmful to the environment, the contribution

from tire emissions is essentially negligible given current and projected future engine emissions. This conclusion is consistent with Bennett et al. 2011. A second avenue of research for tire emissions could be to better understand the tire material that is deposited on the runway during landings. Material could be collected from touchdown areas of landing runways and analyzed for mass and composition. Some of this material may end up in runway runoff and get transported to the airport grounds and perhaps into groundwater. Further, airports clean their runways, and the amount of tire wear material could be tracked and its destination determined. This is not an air pollution issue but possibly a groundwater and waste disposal issue.

3.2.3 Brakes

With regard to brake emissions, the research team cannot quantify an average emissions level. However, after the dedicated field study, the team can conclude that brake emissions are less observable than tire emissions. Because tire emissions are so small compared with engine emissions, these emissions are also negligible compared with engine emissions. If a quantified number is required, the team suggests that future tests be performed at a brake testing facility, where measurements very close to a braking system could be carried out. If such a number is not required, the team does not advocate further work in this area. Translating measurements at a brake-testing facility to emissions during aircraft operation may be difficult and uncertain, but such a test could conceivably be used to try to put some more quantitative bounds on brake emissions levels. However, the tests performed under this study strongly indicate that sensitive equipment cannot detect brake emissions, even when very low levels of tire emissions were measured and quantified. This conclusion is not inconsistent with Bennett et al. (2011), where brake dust was found adhering to the aircraft wheel cowling and underbody. Apparently, little is suspended in the air at levels even commensurate with the low level of tire emissions.

Bibliography

Bennett, M., Christie, S. M., Graham, A., Thomas, B. S., Vishnyakov, V., Morris, K., Peters, D. M., Jones, R., and Ansell, C., "Composition of smoke generated by landing aircraft." *Environ. Sci. Technol.*, 2011, 3533–3538.

Canagaratna, M. R., Jayne, J. T., Jimenez J. L., Allan J. D., Alfarra, M. R., Zhang Q., Onasch, T. B., Drewnick, F., Coe, H., Middlebrook, A., Delia, A., Williams, L. R., Trimborn A. M., Northway, M. J., DeCarlo, P. F., Kolb, C. E., Davidovits, P., Worsnop, D. R., "Chemical and Microphysical Characterization of Ambient Aerosols with the Aerodyne Aerosol Mass Spectrometer." *Mass Spectrom. Rev.,* 26, 2007, 185–222.

Hagen, D. E., Lobo, P., Whitefield, P. D., Trueblood, M. B., Alofs, D. J., Schmid, O., "Performance Evaluation of a Fast Mobility-Based Particle Spectrometer for Aircraft Exhaust." *Journal of Propulsion and Power,* 25, 2009, 628–634.

Herndon, S. C., Zahniser, M. S. Nelson, D. D., Shorter, J. H., McManus, J. B., Jimenez, R., Warneke, C., and de Gouw, A. J. "Airborne measurements of HCHO and HCOOH during the New England Air Quality Study 2004 using a pulsed quantum cascade laser spectrometer." *J. Geophys. Res.,* 112, 2007, D10S03.

Herndon, S. C., Jayne, J. T., Lobo, P., Onasch, T., Fleming, G., Hagen, D. E., Whitefield, P. D., and Miake-Lye, R. C., "Commercial Aircraft Engine Emissions Characterization of In-Use Aircraft at Hartsfield-Jackson Atlanta International Airport." *Environmental Science and Technology,* 42, 2008, 1877–1883.

Herndon, S., Wood, E., Franklin, J., Miake-Lye, R., Knighton, W. B., Babb, M., Nakahara, A., Reynolds, T., Balakrishnan, H., *ACRP Report 63: Measurement of Gaseous HAP Emissions from Idling Aircraft as a Function of Engine and Ambient Conditions.* Transportation Research Board of the National Academies, Washington, DC, 2012, 112 pp.

Jayne, J. T., Leard, D. C., Zhang, X. , Davidovitz, P., Smith, K. A., Kolb, C. E., Worsnop, D. R., "Development of an Aerosol Mass Spectrometer for Size and Composition Analysis of Submicron Particles." *Aerosol Sci. Technol.,* 33(1–2), 2000, 49–70.

Jimenez, R., Herndon, S. C., Shorter, J. H., Nelson Jr., D. D., McManus, J. B., and Zahniser, M. "Atmospheric trace gas measurements using a dual quantum-cascade laser mid-infrared absorption spectrometer." *SPIE Proceedings,* 5738, 2005, 318–331.

Kim, B., Rachami, J., Robinson, D., Robinette, B., Nakada, K., Arunachalam, S., Davis, N., Haeng Baek, B., Shankar, U., Talgo, K., Yang, D., Hanna, A. F., Wayson, R. F., Noel, G., Cliff, S. S., Zhao, Y., Hopke, P. K., Kumar, P., *ACRP Report 71: Guidance for Quantifying the Contribution of Airport Emissions to Local Air Quality.* Transportation Research Board of the National Academies, Washington, DC, 2012, 78 pp.

Kinsey, J. S., Timko, M. T., Herndon, S. C., Wood, E. C., Yu, Z., Miake-Lye, R. C., Lobo, P., Whitefield, P., Hagen D., Wey, C., Anderson, B. E., Beyersdorf, A. J., Hudgins, C. H., Thornhill, K. L., Winstead, E., Howard, R., Bulzan, D. I., Tacina, K. B., and Knighton, W. B. "Determination of the emissions from an aircraft auxiliary power unit (APU) during the Alternative Aviation Fuel Experiment (AAFEX)." *Journal of the Air and Waste Management Association,* Vol. 62, No. 4, 2012, 420–430.

Knighton, W. B., Rogers, T. M., Anderson, B. E., Herndon, S. C., Yelvington, P. E., and Miake-Lye, R. C., "Quantification of Aircraft Engine Hydro-carbon Emissions Using Proton Transfer Reaction Mass Spectrometry." *J. Propul. Power,* 23, 2007, 949–958.

Lobo, P., Whitefield, P. D., Hagen, D. E., Herndon, S. C., Jayne, J. T., Wood, E. C., Knighton, W. B., Northway, M. J., Miake-Lye, R. C., Cocker, D., Sawant, A., Agrawal, H., Miller, J. W., *The Development of Exhaust Speciation Profiles for Commercial Jet Engines.* ARB Contract No. 04-344 Report, California Air Resources Board, 2007a.

Lobo, P., Hagen, D. E., Whitefield, P. D., Alofs, D. J., "Physical Characterization of Aerosol Emissions from a Commercial Gas Turbine Engine." *Journal of Propulsion and Power,* 23, 2007b, 919–929.

Lobo, P., Hagen, D. E., Whitefield, P. D., "Measurement and Analysis of Aircraft Engine PM Emissions downwind of an active runway at the Oakland International Airport." Atmospheric Environment, Vol. 61, 2012, 114–123.

Onasch, T. B., Trimborn, A., Fortner, E. C., Jayne, J. T., Kok, G. L., Williams, L. R., Davidovitz, P., Worsnop, D. R., "Soot Particle Aerosol Mass Spectrometer: Development, Validation and Initial Application." *Aerosol Sci. Technol.,* 46(7), 2012, 804–817.

Petzold, A., Schonlinner, M., "Multi-angle absorption photometry—a new method for the measurement of aerosol light absorption and atmospheric black carbon." *J. Aerosol Sci.,* 35, 2004, 421–441.

Petzold, A., Schloesser, H., Sheridan, P. J., Arnott, W. P., Ogren, J. A., Virkkula, A., "Evaluation of Multi-Angle Absorption Photometry for Measuring Aerosol Light Absorption." *Aerosol Science and Technology,* 39, 2005, 40–51.

Reavell, K., Hands, T., and Collings, N., *A fast response particulate spectrometer for combustion aerosols.* SAE Technical Paper, 2002, 2002-01-2714.

Shorter, J. H., Herndon, S. C., Zahniser, M. S., Nelson, Jr., D. D., Wormhoudt, J., Demerjian, K. L., and Kolb, C. E., "Real-time Measurements

of Nitrogen Oxide Emissions from In-use New York City Transit Buses using a Chase Vehicle." *Environmental Science and Technology,* 39, 2005, 7991–8000.

Webb, S., Whitefield, P. D., Miake-Lye, R. C., Timko, M. T., Thrasher, T. G., *ACRP Report 6: Research Needs Associated with Particulate Emissions at Airports.* Transportation Research Board of the National Academies, Washington, DC, 2008, 34 pp.

Whitefield, P. D., Lobo, P., Hagen, D. E., Timko, M. T., Miake-Lye, R. C., Taylor, C., Ratliff, G., Lukachko, S., Sequeria, C., Hileman, J., Waitz, I., Webb, S., Thrasher, T. G., Ohsfeldt, M. R., Kaing, H. K., Essama, S. C., *ACRP Report 9: Summarizing and Interpreting Aircraft Gaseous and Particulate Emissions Data.* Transportation Research Board of the National Academies, Washington, DC, 2008, 59 pp.

Yu, Z., Ziemba, L. D., Onasch, T. B., Herndon, S. C., Albo, S. E., Miake-Lye, R., Anderson, B. E., Kebabian, P. L., Freedman, A., "Direct Measurement of Aircraft Engine Soot Emissions Using a Cavity-Attenuated Phase Shift (CAPS)-Based Extinction Monitor." *Aerosol Sci. Tech.,* 45, 2011, 1319–1325.

Yu, Z., Herndon, S. C., Ziemba, L. D., Timko, M. T., Liscinsky, D. S., Anderson, B. E., and R. C. Miake-Lye, "Identification of Lubrication Oil in the Particulate Matter Emissions from Engine Exhaust of In-Service Commercial Aircraft." *Environ. Sci. Technol.,* 46, 2012, 9630–9637.

Glossary of Terms, Acronyms, and Abbreviations

AAFEX: Alternative Aviation Fuel Experiment; an aircraft emissions measurement campaign using alternative aviation fuels conducted January 20 to February 3, 2009, at NASA Dryden Aircraft Operation Facility

advected plume: wind-transported exhaust plume, subjected to local meteorological conditions

aerodynamic diameter: the diameter of an equivalent unit density sphere with the same settling velocity in still air as the particle in question

aircraft gas turbine engine: any gas turbine engine used for aircraft propulsion or for power generation on an aircraft, including those commonly called turbojet, turbofan, turboprop, or turboshaft type engines[1]

AMS: aerosol mass spectrometer

APEX: a series of aircraft engine emissions field measurement campaigns including APEX1, Delta Atlanta-Hartsfield Study, JETS-APEX2, and APEX3

APU: auxiliary power unit, a small gas turbine engine that provides (bleed air) aircraft power for pneumatic systems, ventilation, and heating

BC: black carbon

CAPS: cavity attenuation phase shift

CH_4: methane

C_2H_2: acetylene

C_2H_4: ethylene

C_2H_6: ethane

C_4H_{10}: butane

$C_{24}H_{14}$: dibenzopyrene

CO: carbon monoxide

CO_2: carbon dioxide

Cu: copper

elemental carbon: the refractory carbon found in combustion-generated particulate matter. Also known as graphitic carbon[1]

EGT: exhaust gas temperature

EI: emissions index, the emissions of a given constituent per unit of fuel burned (EIm—emission index (mass) in g/kg fuel; EIn—emission index (number) in number of particles/kg fuel)

engine exit plane: any point within the area of the engine exhaust nozzle at an axial distance within 0.5 diameters (or equivalent, if not circular) downstream from the outer edge of the nozzle

Fe: iron

GMD: geometric mean diameter

GSD: geometric standard deviation

HAPs: hazardous air pollutants, 188 pollutants that the Clean Air Act Amendments of 1990 required the EPA to regulate. The complete list of pollutants can be found on the EPA website: http://www.epa.gov/ttn/atw/orig189.html (for a complete list, see Appendix C—The Clean Air Act Amendments of 1990 List of Hazardous Air Pollutants).

H_2: hydrogen

HCHO: formaldehyde

HCOOH: formic acid

HC: hydrocarbon

line loss: percent of particles lost during transit through a given sample line. Particle loss mechanisms include impaction,

[1] Society of Automotive Engineers Aerospace Information Report 5892 copyright © 2007 SAE.

diffusion, settling (gravitational), and thermophoresis (thermodiffusion).

MAAP: multi-angle absorption photometer

mass-based emission index: the mass of emissions of a given constituent per thousand mass units of fuel burned (e.g., g/kg fuel). Also total mass of particulate emissions in the same units.

N_2: nitrogen gas

NH_3: ammonia

Ni: nickel

NO: nitrogen oxide

NO_2: nitrogen dioxide

NO_x: nitrogen oxides

non-volatile particles: particles that exist at engine exit plane temperature and pressure conditions[2]

nucleation: the process of initial formation of a particle from vapor. This process is usually facilitated by the presence of small particles called condensation nuclei, which serve as sites for condensation.[3]

OPS: optical particle spectrometer

organic carbon: often abbreviated as OC, is a major component of particulate carbon and is composed of many compounds, most of which partition between the gas and aerosol phases at ambient conditions

parameterization: expression in terms of statistically representative characteristics.

parts per million (ppmv): the unit volume concentration of a gas per million unit volumes of the gas mixture of which it is part. (Also applicable to mass measurements and referred to as ppmm)[4]

PM_{10}, $PM_{2.5}$, $PM_{1.0}$: regulatory designations of particulate matter less than or equal to 10 micrometers, 2.5 micrometers, and 1.0 micrometers, respectively, in diameter. These measures are similar to the terms coarse, fine, and ultrafine, respectively.

PMex: particle extinction monitor

PTR-MS: proton transfer reaction mass spectrometer

RPM: revolutions per minute

Smoke: small gas-borne solid particles, including but not limited to black carbonaceous material from the burning of fuel, which in sufficient concentration create visible opacity

smoke number: often abbreviated as SN, the dimensionless term quantifying smoke emission. SN increases with smoke density and is rated on a scale from 0 to 100. SN is evaluated for a sample size of 16.2 kg of exhaust gas/m^2 (0.0239 lb/in^2) of filter area.

Soluble mass fraction: the fraction of the aerosol mass that is soluble in water

SO_2: sulfur dioxide

total carbon: the sum of elemental carbon and organic carbon[5]

transients: momentary or temporary variation in a variable of interest, e.g., engine power, ambient pressure, temperature.

UHC: unburned hydrocarbon

VOC: volatile organic compound

volatile particles: particles formed from condensable gases after the exhaust has been cooled to below engine exit conditions

---

[2] Society of Automotive Engineers Aerospace Information Report 5892 copyright © 2007 SAE.

[3] Baron P.A. and Willeke, K. (Eds.) *Aerosol Measurementa Principles, Techniques and Applications*, 2nd Edition, John Wiley and Sons, New York, 2001.

[4] Society of Automotive Engineers Aerospace Information Report 5892 copyright © 2007 SAE.

[5] Society of Automotive Engineers Aerospace Information Report 5892 copyright © 2007 SAE.

APPENDIX A

Literature Survey and Bibliography

A.1 Literature Survey

A.1.1 Aircraft Auxiliary Power Unit Emissions

An aircraft auxiliary power unit (APU) is a small gas-turbine engine usually mounted in the tail cone of the aircraft, behind the rear pressure bulkhead. It runs on fuel from the main fuel tanks that also supply fuel to the main aircraft engines. The APU provides electricity and pre-conditioned air when the aircraft is taxiing or parked at the gate and bleed air for main engine start as well as in-flight power backup. Average operating time for an APU varies between 45 minutes for short-haul flights and 75 minutes for long-haul flights (ICAO 2007). Generally, an APU has the following three modes of operation:

- no load/idle (start up),
- normal running (Environmental Control System [ECS]), and
- high load (main engine start).

The International Civil Aviation Organization (ICAO) sets emissions standards for turbojet and turbofan engines greater than 26.7 kilo Newtons (kN) of thrust; but not turboprop, turboshaft, or piston engines, or APUs. Limited information is publicly available on PM emissions from APUs. ICAO prescribes a technique to estimate APU emissions for NO_x, CO, unburned hydrocarbon (UHC), and PM based on averaged proprietary engine-specific values obtained from APU manufacturers (ICAO 2007).

The FAA's Emissions and Dispersion Modeling System (EDMS) includes a database of APUs that associates APU model with various commercial aircraft models. The database includes some limited APU emissions factors but nothing as extensive as the data available for aircraft main engines. A study for the U.S. Air Force estimated APU emissions for both commercial and military applications for each stage of the landing takeoff (LTO) cycle based on emissions data from EDMS (Wade 2002).

The Zurich Airport published a report on APU emissions, which referenced fuel flow data and emission factors for NO_x, CO, and hydrocarbon (HC) for different APU operation modes (Fleuti and Hofmann 2005). Their APU database was established in 1994, based on the same source as the EDMS database, supplemented with additional data from APU manufacturers. The APU emissions at Zurich airport are calculated using the standard approach defined by ICAO (ICAO 2007) using average emission factors. The calculated average emissions factors for various APU types in terms of NO_x, CO and HC were 6.5 g/kg fuel, 7.3 g/kg fuel, and 0.7 g/kg fuel, respectively. Emission factors for PM were not reported. A field study of gaseous emissions (NO_x and CO) from commercial APUs operating at different conditions concluded that the emissions indices for the APU emissions were the same order of magnitude as main aircraft engine emissions (Schäfer et al. 2003).

More recently, an in-depth investigation of PM and gas phase emissions from a Honeywell (formerly Garrett) Model GTCP85-98CK APU were measured with varying load conditions as part of the AAFEX (Alternative Aviation Fuels Experiment) study. This study found that PM number and mass-based emission indices both decreased with increasing APU load (Kinsey et al. 2012) and that PM mass-based emissions indices (grams of PM per kilogram of fuel burned) are higher for APUs compared with most engines in the current commercial fleet by as much as a factor of 10. This finding was supported by data from another study characterizing the PM and gaseous emissions of a recommissioned Artouste Mk113 APU (Lobo et al. 2012).

Table A.1 presents a summary of common aircraft with their associated APUs. This is based on the EDMS database, supplemented with data from other references.

Table A.1. Aircraft and associated APUs.

Aircraft Category	Example Aircraft	Representative APU
Jumbo Wide Body	Boeing 747; Airbus A330	GTCP 331-350; GTCP 660; PW 901
Wide Body	A300; A310; B767; MD11; DC10	GTCP 330-200; GTCP 331-500; TSCP 700;
Narrow Body	A318; A319; A320; A321; B737; B757; MD80; DC8; DC9; EMB170; EMB175	131-9; GTCP 36; GTCP 85; GTCP 331-200; APS2000; APS2300; APS3200
Regional Jet	CRJ100; CRJ200; CRJ700; CRJ900; EMB135; EMB140; EMB145; Cessna Citation III	GTCP36; GTCP85; APS500

A.1.2 Tire Emissions

This subsection discusses information from the literature on the composition of aircraft tires, which was used to plan the sampling and analysis protocols in the winter and summer measurement campaigns.

A.1.2.1 Tire Composition

Several sources review the composition and construction of tires (ChemRisk and DIK 2008; Overhoff 2004; Thorpe and Harrison 2008; Wik and Dave 2009), including data reports by the aircraft tire manufacturers including Good Year Tire and Rubber Company and Michelin Aircraft Tire. Composition data specific to aircraft tires is not available in the open literature, nor are precise data for automotive tire composition. Nonetheless, some general trends can be described. Tires contain a wide range of polymer rubbers, fillers, metal (steel), softeners, and anti-aging and vulcanizing agents. Percentage wise, the contributions of these material types vary; however, polymer rubbers (roughly 40–60%) and fillers (20–30%) are always the most abundant materials in tires. Typical tire polymers include natural rubber (biological homopolymer of isoprene), styrene-butadiene rubber (SBR), and polybutadiene rubber (PR). Carbon black is the most common rubber filler material used in tires. Carbon black is a carbon material composed of agglomerated carbon spherules produced from flame synthesis of carbon-rich feedstocks. The purpose of the carbon black filler is to increase rubber hardness and stiffness. High aromatic oils (HA-oils) are used as plasticizing agents (also termed extender or process oils) in road tires. HA-oils contain a high percentage of polyaromatic hydrocarbons and their use in road tires has come under scrutiny in the E.U. The use of mild extract solvents (MES) and treated distillate aromatic extracts (TDAE) as tire softeners is increasing.

Vulcanization is required to improve rubber stiffness and many of the chemicals present in rubber are required for the vulcanizing process (Overhoff 2004). The rubber-insoluble sulfur used in rubber making is an amorphous polymeric form with molecular weights of 100,000–300,000. In addition to the sulfur polymers, a range of activators, accelerators, and—for certain formulations—retarders are used during vulcanization. *Accelerators* control the vulcanization initiation time, rate of vulcanization, and number and type of sulfur cross-links that form. Typical organic accelerators include sufenamides and thiazoles (Wik and Dave, 2009), though many other accelerators have been used and use of a mixture of accelerators is common practice (Overhoff 2004). *Activators* are chemicals that increase the rate of vulcanization by reacting first with the accelerators to form rubber-soluble complexes. The most common activators are combinations of zinc oxide and stearic acid. *Retarders* delay the initial onset of cure to allow sufficient time to process the raw rubber. Organic acids and anhydrides are the most common retarders.

In contrast to road tires, aircraft tires are designed to carry very heavy loads, at extremely high speeds, for short (seconds) periods of time. Cost is probably not as important a driving force in aircraft tires as it is in road tires. Components that tend to increase the load-bearing capabilities of the tire material should be expected to be more abundant in aircraft tires than in road tires. Kevlar®, a highly cross-linked para-aramid synthetic fiber polymer, is a specific component that may be used in aircraft tires but that is not typically found in road tires.

A.1.2.2 Tire Wear PM Characteristics

An abundant literature exists on the tire wear PM emissions of road tires (Aatmeeyata and Sharma 2010; Adachi and Tainosho 2004; Boonyatumanond et al. 2007; Camatini et al. 2001; Councell et al. 2004; Dahl et al. 2006; Hussein et al. 2008; Kaul and Sharma 2009; Kumata et al. 1997; Sarkissian 2007; Thorpe and Harrison 2008; Wik and Dave 2009); however, the literature on aircraft tire wear PM emissions is lacking. Therefore, understanding aircraft tire wear PM can only be inferred by review of the road tire PM emissions literature. Wik and Dave (2009) summarize reports on the annual tire wear par-

ticle emissions for E.U. countries, ranging from $7.3x10^6$ kg (Denmark) to $600x10^6$ kg (U.S.A.). The ratio of tire abrasion material that remains on the road to that formed into aerosol particles is an important quantity. Very early reports on tire wear emissions concluded that less than 5% of the tire wear particles are airborne (Cadle and Williams 1978; Pierson and Brachazek 1974) and less than 1% of the abraded rubber is emitted in the form of gaseous emissions (Cadle and Williams 1978). Nonetheless, Luekewille et al. (2001) suggest that tire abrasion PM may be the largest source of non-exhaust PM, second only to re-suspended road dust.

Tire wear particles have been suggested as a source of PM (Dahl et al. 2006; Hussein et al. 2008; Thorpe and Harrison 2008; Wik and Dave 2009), zinc, (Adachi and Tainosho 2004; Councell et al. 2004; Hjortenkrans et al. 2007), and PAHs (Aatmeeyata and Sharma 2010; Boonyatumanond et al. 2007; Manchester-Neesvig et al. 2003; Rogge et al. 1993) in the environment. Tire wear can generate PM emissions by three mechanisms: (1) mechanical abrasion, (2) evaporation and recondensation of volatile components, and (3) pyrolysis of non-volatile components. Pierson and Brachaczek (1974) reported that only 10% of the mass of tire wear PM was present in particles smaller than 3 microns. Pierson and Brachaczek were probably describing particles formed by mechanical abrasion processes. Kaul and Sharma (2009) formed tire wear particles in a fully enclosed laboratory-scale facility and reported that less than 0.1% of tire wear particle mass consisted of particles smaller than 10 microns in diameter. More recently, Dahl et al. (2006) observed formation of sub-micron fine particles in the 15–50 nm size mode in a road simulator study. Dahl et al. (2006) concluded that the fine particle source was probably the plasticizing oils or the carbon black fillers. Camatini et al. (2001) studied tire wear PM using electron microscopy and x-ray spectroscopy and found that its microstructure consisted of 15-nm agglomerates of 1.5-nm primary filler spherules—consistent with the report by Dahl et al. (2006). Therefore, tire wear PM mass may be dominated by particles larger than 10 microns, but tire wear PM number may be dominated by particles smaller than 1 micron.

Release of PAHs may be attributed to either the plasticizer oils or rubber pyrolysis. Forensic evidence of tire materials removed from road surfaces indicates that the road surface material contains compounds not present in the tire itself, indicating that chemical reactions occur during the braking process (Sarkissian 2007). Therefore, tire pyrolysis may be an important mechanism for PM formation during braking events for road traffic. Road traffic braking may be similar to the spin up of aircraft tires during landing, where the interaction of the tire and the roadway occurs when the vehicle is operating at a speed that does not match the rotational speed of the tire.

Although literature on rubber tire pyrolysis is abundant, the temperatures and residence times studied in the literature are typically optimized for converting the tire material to liquid or gaseous fuels; therefore, applying the rubber tire pyrolysis literature to the tire braking problem is not straightforward and only some general trends can be extracted. During tire pyrolysis, rubber polymers will be degraded. To first order, the primary products will be the monomers (e.g., styrene, butadiene, and isoprene [Kaminsky and Mennerich 2001]). Depending on the conditions, additional species including PAHs can be formed during pyrolysis of tire materials (Kwon and Castaldi 2006).

Apportioning PM mass to various exhaust and non-exhaust sources is difficult. Hence, substantial work has been performed to determine biomarker compounds that can be associated exclusively with tire wear PM. Although no compound is completely without ambiguity, several researchers (Kumata et al. 1997; Kumata et al. 2002) indicate that benzothiazole and benzothiazole derivatives seem to provide a reasonably interference-free biomarker for tire PM. Camatini et al. (2001) indicate the concurrence of particle morphology—specifically the agglomerated structure associated with carbon black—and zinc can be used as a conclusive indicator of tire wear PM. Additionally, PAH content of tire wear particles—specifically pyrene and benzo[ghi]perylene (Aatmeeyata and Sharma 2010)—may be sufficient to serve as a biomarker for tire wear PM.

Based on a straightforward review of the road tire PM literature, aircraft tire emissions might be differentiated from exhaust emissions by (1) a larger characteristic PM size, (2) the presence of zinc, (3) the presence of benzothiazole, and (4) increased concentrations of styrene, butadiene, and PAHs relative to pure exhaust. As a cautionary note, applying knowledge gained from analyzing the road tire wear PM literature to the aircraft application is not straightforward. The load and speed conditions encountered by aircraft tires are much more extreme than those encountered by road tires. Therefore, aircraft tire PM may tend to be smaller than road tire PM. Additionally, chemical pyrolysis may be more important during aircraft braking events than in road tire braking events. Finally, while the same primary components are present in aircraft and road tires, their relative contributions are likely different. Therefore, a robust sampling protocol should take into account the potential for aircraft tire wear PM to be smaller than road tire wear PM and to have slightly different chemical composition—both due to differences in tire composition and chemical pyrolysis accompanying the braking event.

A.1.3 Brake Emissions

This subsection discusses information obtained from the literature on the composition of aircraft brakes, which was used to plan the sampling and analysis protocols in the winter and summer measurement campaigns.

Table A.2. Brake components and materials.

Brake Component	Proportions	Materials
Fibers	6–35%	various metals, carbon, glass, Kevlar
Abrasives	10%	aluminum oxide; iron oxides; quartz, silica, zirconium silicate
Lubricants	5–29%	antimony trisulfide; copper; brass; graphite; metal oxides; metal sulfides
Fillers and reinforcements	15–70%	barium sulfate; zinc oxide; cashew nut shell oil; rubber particles
Binding materials	20–40%	phenolic and modified resins; metallic alloys of Cu, iron (Fe) and nickel (Ni)

Aircraft brakes are designed to stop an aircraft's forward momentum through friction, converting a large amount of kinetic energy into heat in a very short period of time. Aircraft brakes consist of multiple disk pairs, commonly referred to as the brake heat sink (Tatarzycki and Webb 1992). When the brakes are applied, friction between the brake discs and linings causes wear and the resulting PM emissions contribute to the overall emissions at the airport. The brake wear PM characteristics are influenced by factors such as brake material composition, heat sink mass, energy absorbed by the brakes, surface velocity of the friction interfaces, and aircraft deceleration requirements (Tatarzycki and Webb 1992). Information on PM emissions from aircraft brakes is proprietary and not available in the public domain. There is, however, abundant information on automotive brake emissions and studies on measuring these emissions in the urban environment (Garg et al. 2000; Sanders et al. 2003; Lough et al. 2005; Hjortenkrans et al. 2007; Iijima et al. 2007, 2008; Thorpe and Harrison 2008; Bukowiecki et al. 2009; Gietel et al. 2010, Wahlström et al. 2010) and this information was used to develop the sampling and measurement plan for aircraft brake wear PM characterization.

A.1.3.1 Brake Composition

Although the composition and relative proportions of brake components can vary based on the application (e.g., automobile brakes vs. aircraft brakes), brakes in general are found to consist of the following five components: fibers, abrasives, lubricants, fillers and reinforcements, and binding materials. Table A.2 provides a list of commonly used materials for each brake component and their typical proportions (Blau 2001; Thorpe and Harrison 2008).

Aircraft brakes can be classified into two categories: steel brakes and carbon brakes. They generally employ three different kinds of friction materials: sintered metal, carbon/carbon (C/C) composites, and organic materials (Tatarzycki and Webb 1992).

There are four major aircraft brake manufacturers: Messier-Bugatti, Goodrich, Honeywell, and Meggitt Aircraft Braking Systems. Table A.3 presents a summary of common aircraft with their associated brake material based on information obtained from the manufacturers' websites.

Steel brakes are heavier and have a higher wear rate but cost less per brake landing when compared with carbon brakes. Steel brakes are typically used on smaller, short-haul commercial aircraft and carbon brakes on larger, long-haul commercial aircraft. Recently, improvements in the carbon brake manufacturing process have reduced the cost per landing of carbon brakes such that they are now competitive in terms of cost with steel brakes (Allen et al. 2009). Commercial aircraft such as the A310, A318, A319, A320, A321, A330, A340, B747, B757, B767, B777, MD-11, and MD-90 use carbon brakes (Blau 2001; Allen et al. 2009; Messier-Bugatti 2010). Steel brakes typically use sintered metal friction material while carbon brakes use C/C

Table A.3. Aircraft and brake materials.

Aircraft Category	Example Aircraft	Brake Material
Wide Body	A300; A310; A330; A340; A380; B747; B767; B777; MD11	Carbon
	DC10	Steel
Narrow Body	A318; A319; A320; A321; N737NG; B757; CRJ-1000; EMB170/175; EMB 190/195; MD90	Carbon
	B737-600/700/800/900; CRJ100; CRJ200; CRJ700; CRJ900; DC9; MD80;	Steel

composites as friction material. Organic friction materials are used on older and smaller aircraft (Tatarzycki and Webb 1992).

The sintered metal friction materials are mixtures of metallic (primarily, copper and iron) and non-metallic powders. The base mixture is modified by adding graphite, silicon, and high-temperature lubricants (e.g. molybdenum disulfide). C/C composite friction materials are produced from high-density carbon fibers, made from either polyacrylonitrile or pitch, embedded in a carbon matrix (Tatarzycki and Webb 1992). The C/C composite materials are more commonly used in high-performance brakes due to their ability to absorb large quantities of energy emitted as heat and withstand large stresses that are experienced when the aircraft's brakes are applied.

A.1.3.2 Brake Wear PM Characteristics

For steel brakes, the most significant wear is observed during aircraft landings, while for carbon brakes, aircrafts stops or snubs during taxi contribute to large brake wear (Tatarzycki and Webb 1992; Allen et al. 2009). Currently, information on PM brake wear characteristics for aircraft brakes is not available; however, studies on automotive brake wear PM emissions can provide some insight into measuring PM emissions from aircraft brakes, since the composition of brake material is similar.

Several studies have investigated PM emissions from automobile brakes in brake dynamometer facilities (Garg et al. 2000; Sanders et al. 2003; Iijima et al. 2007, 2008). These facilities permit PM measurements in an environment where several brake wear conditions can be tested without the influence of external factors. The PM size distributions from automobile brake wear are reported to be bimodal in nature with a primary mode < 0.5 μm and a secondary mode 1–10 μm (Garg et al. 2000; Sanders et al. 2003; Lough et al. 2005; Iijima et al. 2007; Wahlström et al. 2010). Elemental composition of the PM samples measured by using inductively coupled plasma mass spectrometry (ICP-MS) techniques reveals the presence of several metallic species (Lough et al. 2005; Iijima et al. 2007, 2008). Antimony (Sb) and copper (Cu) are reported to be important indicators of brake wear (Lough et al. 2005; Hjortenkrans et al. 2007; Iijima et al. 2007, 2008; Thorpe and Harrison 2008; Bukowiecki et al. 2009; Gietel et al. 2010). In some cases, barium (Ba) in large concentrations has also been observed as being indicative of brake wear (Sanders et al. 2003; Gietel et al. 2010; Wahlström et al. 2010).

The literature review of automobile brake PM emissions provides a basis for measurements of aircraft brake PM. Specifically, the presence of Sb, Cu, and Ba will be key indicators of brake wear, particularly for those smaller aircraft that use steel brakes. For aircraft that use carbon brakes, the most abundant PM is likely to be carbonaceous material. Specific markers for carbon brakes are not available. However, for both carbon and steel brakes, PM size distributions and total mass were monitored, and the data was analyzed for PM that does not correlate with exhaust CO_2 emissions, but which occurs in synchrony with braking events.

A.1.4 Fleet Mix

The U.S. commercial aircraft fleet was analyzed to determine a sufficient number and mix of aircraft to ensure a representative sample of APUs, tires, and brakes are included in the measurement campaign. The Department of Transportation's Bureau of Transportation Statistics collects data on aircraft departures at all commercial airports. It publishes this data annually in the Airport Activity Statistics of Certificated Air Carriers. The most recent year for which complete data was available at the start of this project was 2008.

Data on total U.S. departures by aircraft type was extracted from this database. The aircraft types were then ranked according to frequency of departures. Twenty-three aircraft models represent more than 90% of all commercial aircraft departures and 41 models represent more than 95%. Among these 41 aircraft models, 10 different APU models are employed. This group of aircraft also includes a representative mix of jumbo wide body (A330, B747), wide body (A300, B767), narrow body (A320, B737), and regional jet (CRJ700, EMB145) aircraft.

A.2 Bibliography for the Literature Survey

A.2.1 Aircraft Auxiliary Power Unit Emissions

Fleuti, E., and Hofmann, P. *Aircraft APU Emissions at Zurich Airport.* Flughafen Zürich AG, January 2005.

> The APU emissions at Zurich airport are calculated using average emission factors from APU manufacturers. The calculated average emissions factors for various APU types in terms of NO_x, CO and HC were 6.5 g/kg fuel, 7.3 g/kg fuel and 0.7 g/kg fuel, respectively. Emission factors for PM were not reported.

International Civil Aviation Organization (ICAO). *Airport Air Quality Guidance Manual,* preliminary ed., 2007.

> Prescribes a technique to estimate APU emissions for NO_x, CO, UHC and PM based on averaged proprietary engine-specific values obtained from APU manufacturers.

Kinsey, J. S., Timko, M. T., Herndon, S. C., Wood, E. C., Yu, Z., Miake-Lye, R. C., Lobo, P., Whitefield, P., Hagen D., Wey, C., Anderson, B. E., Beyersdorf, A. J., Hudgins, C. H., Thornhill, K. L., Winstead, E., Howard, R., Bulzan, D. I., Tacina, K. B., and Knighton, W. B. "Determination of the emissions from an aircraft auxiliary power unit (APU) during the Alternative Aviation Fuel Experiment (AAFEX)." *Journal of the Air and Waste Management Association,* Vol. 62, No. 4, 2012, 420-430.

Gas phase and PM emissions from a Honeywell (formerly Garrett) Model GTCP85-98CK APU were measured with varying load conditions based on exhaust gas temperature (EGT). PM number and mass-based emission indices both decreased with increasing EGT (or APU load). PM mass-based emission index decreased from 600 mg/kg fuel to 200 mg/kg fuel and the PM number-based emission index decreased from $6x10^{15}$ to $2x10^{15}$ when EGT was varied from 350°C to 625°C.

Lobo, P., Rye, L., Williams, P. I., Christie, S., Uryga-Bugajska, I., Wilson, C. W., Hagen, D. E., Whitefield, P. D., Blakey, S., Coe, H., Raper, D., and Pourkashanian, M. "Impact of Alternative Fuels on Emissions Characteristics of a Gas Turbine Engine—Part 1: Gaseous and Particulate Matter Emissions." *Environmental Science and Technology,* Vol. 46, No. 19, 2012, 10805–10811.

Gas phase and PM emissions from a recommissioned Artouste Mk113 APU were measured with varying load conditions. PM number and mass-based emission indices both increased from idle to full power (445°C to 460°C EGT). PM number-based emission index varied from 1.2 ± 0.4 $x10^{16}$ #/kg fuel to 1.9 ± 0.6 $x10^{16}$ #/kg fuel. PM number-based emission index increased from 50.7 ± 14.1 mg/kg fuel to 188.3 ± 59.5 mg/kg fuel.

Schäfer, K., Jahn, C., Sturm, P., Lechner, B., and Bacher, M. "Aircraft emission measurements by remote sensing methodologies at airports." *Atmospheric Environment,* 37, 2003, 5261–5271.

Gaseous emissions (NO_x and CO) of seven commercial APUs at different operating conditions were measured. This study concluded that the emission indices of APUs are in the same order of magnitude as the emission indices of main engines. No measurements of PM emissions from APUs were made.

Wade, M. *Aircraft/Auxiliary Power Unit/Aerospace Ground Support Equipment Emission Factors,* IERA-RS-BR-SR-2003-0002, October 2002.

A list of commercial APUs and the emission factors for NO_x, CO, HC, and PM are presented for each stage of the landing takeoff (LTO) cycle for several APU models.

A.2.2 Tire Emissions

Aatmeeyata, Sharma, M. "Polycyclic aromatic hydrocarbons, elemental and organic carbon emissions from tire-wear." *Science of the Total Environment,* 408, 2010, 4563–4568.

Tire-wear is an important source of PAHs, elemental carbon (EC) and organic carbon (OC). The emissions of these pollutants have been studied in an experimental set-up, simulating a realistic road-tire interaction (summer tire-concrete road). Amongst PAHs, pyrene followed by benzo[ghi]perylene are most abundant. The EC and OC composition of tire-wear PM is distinct from emissions PM.

Adachi, K., and Tainosho, Y. "Characterization of heavy metal particles embedded in tire dust." *Environment International,* 30, 2004, 1009–1017.

Tire dust is a significant pollutant, especially as a source of zinc in the urban environment. This study characterizes the morphology and chemical composition of heavy metal particles embedded in tire dust and traffic-related materials (brake dust, yellow paint, and tire tread) as measured by a field emission scanning electron microscope equipped with an energy dispersive X-ray spectrometer (FESEM/ EDX).

Boonyatumanond, R., Murakami, M., Wattayakorn, G., Togo, A., and Takada, H. "Sources of polycyclic aromatic hydrocarbons (PAHs) in street dust in a tropical Asian mega-city, Bangkok, Thailand." *Science of the Total Environment,* 384, 2007, 420–432.

Samples were taken of roadside air, automobile exhaust soot, tires, asphalt, and used engine oil in a tropical Asian mega-city, Bangkok, Thailand, and analyzed for polycyclic aromatic hydrocarbons (PAHs) and hopanes. The concentrations and compositions of PAHs and hopanes were utilized to identify the sources of PAHs in street dust, in which high concentrations of PAHs were reported in their previous study.

Cadle, S., and Williams, R. "Gas and particle emissions from automobile tires in laboratory and field studies." *Rubber Chemistry and Technology,* 52, 1978, 146–158.

Gas and PM emissions from automobiles are studied in a laboratory and field study environment. Less than 5% of the abraded rubber mass is contained in airborne particles and less than 1% is contained in the gas phase.

Camatini, M., Crosta, G. F., Dolukhanyan, T., Sung, C., Giuliani, G., Corbetta, G. M., Cencetti, S., and Regazzoni, C. "Microcharacterization and identification of tire debris in heterogeneous laboratory and environmental specimens." *Materials Characterization,* 46, 2001, 271–283.

X-ray and electron microscopy analysis of tire debris confirming that tire PM is characterized by a carbon black morphology and zinc component.

ChemRisk Inc., and DIK Inc., *State of Knowledge Report for Tire Materials and Tire Wear Particles,* 2008, Pittsburgh, PA, and Hannover, Germany.

A comprehensive review of the materials present in road tires and a summary of the available toxicology literature. Data gaps in the road tire toxicology data are reviewed.

Councell, T. B., Duckenfield, K. U., Landa, E. R., and Callender, E. "Tire-wear particles as a source of zinc to the environment." *Environmental Science & Technology,* 38, 2004, 4206–4214.

The magnitude of road tire wear zinc inputs to airsheds and watersheds is quantified.

Dahl, A., Gharibi, A., Swietlicki, E., Gudmundsson, A., Bohgard, M., Ljungman, A., Blomqvist, G., and Gustafsson, M. "Traffic-generated emissions of ultrafine particles from pavement-tire interface." *Atmospheric Environment,* 40, 2006, 1314–1323.

In a road simulator study, a significant source of sub-micrometer fine particles produced by the road-tire interface was observed. Since the particle size distribution and source strength are dependent on the type of tire used, it is likely that these particles largely originate from the tires, and not the road pavement. The particles consisted mostly of mineral oils from the softening filler and fragments of the carbon-reinforcing filler material (soot agglomerates). The mean particle number diameters were between 15 and 50 nm, similar to those found in light duty vehicle (LDV) tail-pipe exhaust.

Hjortenkrans, D. S. T., Bergback, B. G., and Haggerud, A. V. "Metal emissions from brake linings and tires: Case studies of Stockholm, Sweden 1995/1998 and 2005." *Environmental Science & Technology,* 41, 2007, 5224–5230.

Road traffic has been highlighted as a major source of metal emissions in urban areas. Brake linings and tires are known emission sources of particulate matter to air; the aim of the current study was to follow the development of metal emissions from these sources over the period 1995/1998 and 2005 and to compare the emitted metal quantities with other metal emission sources. Stockholm, Sweden, was chosen as a study site. The calculations were based on material metal concentrations, traffic volume, particle emission factors, and vehicle sales figures. The results for metal emissions from brake linings/tire tread rubber in 2005 were as follows: Cd 0.061/0.47 kg/year, Cu 3800/5.3 kg/year, Pb 35/3.7 kg/year, Sb 710/0.54 kg/year, and Zn 1000/4200 kg/year.

Hussein, T., Johansson, C., Karlsson, H., and Hansson, H. C. "Factors affecting non-tailpipe aerosol particle emissions from paved roads: On-road measurements in Stockholm, Sweden." *Atmospheric Environment,* 42, 2008, 688–702.

A large fraction of urban PM10 concentrations is due to non-exhaust traffic emissions. In this paper, a mobile measurement system has been used to quantify the relative importance of road particle emission and suspension of accumulated dust versus direct pavement wear, tire type (studded, friction, and summer), pavement type, and vehicle speed. The particle number size distribution of the emissions due to road wear by studded tire was characterized by a clear increase in number concentrations of the coarse fraction of aerosol particles, with a geometric mean diameter between 3 and 5 microns.

Kaminsky, W., and Mennerich, C. "Pyrolysis of synthetic tire rubber in a fluidised-bed reactor to yield 1,3-butadiene, styrene and carbon black." *Journal Analytical and Applied Pyrolysis,* Vol. 58–59, April 2001, pp. 803–811.

Main products of the pyrolysis of tires are an aromatic-rich oil and carbon black, which can be reused. While it was possible to obtain only 2–4 wt% of isobutene, the isoprene content reached 22 wt% from natural rubber.

Kaul, A. D. S., and Sharma, M. "Traffic generated non-exhaust particulate emissions from concrete pavement: A mass and particle size study for two-wheelers and small cars." *Atmospheric Environment.* 43, 2009, 5691–5697.

This study aimed to understand the non-exhaust (NE) emission of particles from wear of summer tire and concrete pavement, especially for two wheelers and small cars. A fully enclosed laboratory-scale model was fabricated to simulate road tire interaction with a facility to collect particles in different sizes. A road was cast using the M-45 concrete mixture and the centrifugal casting method. It was observed that emission of large particle non-exhaust emission (LPNE) as well as PM10 and PM2.5 increased with increasing load. The contribution of the PM10 and PM2.5 was smaller compared with the LPNE particles (less than 0.1%).

Kumata, H., Takada, H., and Ogura, N. 2-(4-morpholinyl)-benzothiazole as an indicator of tire-wear particles and road dust in the urban environment. In: Eganhouse RP, editor. *Molecular Markers in Environmental Geochemistry,* 1997, 291–305.

As an indicator of tire wear debris and road dust, 2-(4-morpholinyl)-benzothiazole (24MoBT) was found in environmental samples collected from urban Tokyo in 1989 and 1993/94. 24MoBT existed in tire tread rubber, road dust, runoff particles, river water particles, river sediment and aerosols in the widely varying concentrations (similar to ng g^{-1} and similar to mu g g^{-1}). Comparison of 24MoBT concentrations in tire tread with those in environmental samples showed that tire debris was a significant component of ambient particulate matter.

Kumata, H., Yamada, J., Masuda, K., Takada, H., Sato, Y., Sakurai, T., and Fujiwara, K. "Benzothiazolamines as tire-derived molecular markers: Sorptive behavior in street runoff and application to source apportioning." *Environmental Science & Technology,* 36, 2002, 702–708.

Wash-off and sorptive behaviors of two benzothiazolamines (BTs) [i. e., 2-(4-morpholinyl)-benzothiazole (24MoBT) and N-cyclohexyl-2-benzothiazolamine (NCBA)] have been investigated as possible molecular markers for tire debris and/or road dust transported in highway runoff water. All results indicate that NCBA would be more suitable than 24MoBT as a molecular marker for runoff particles loading the aquatic environment.

Kwon, E., and Castaldi, M. J. *Polycyclic aromatic hydrocarbon (PAH) formation in thermal degradation of styrene butadiene copolymer (SBR);* 2006 May 01–03; Tampa, FL. pp. 79–89.

This study has been initiated to quantify the release of the Polycyclic Aromatic Hydrocarbon (PAH) species from Styrene

Butadiene Copolymer (SBR) during gasification. The identification and quantification has been determined experimentally using Gas Chromatography/Mass Spectroscopy (GC/MS) coupled to a Thermo-Gravimetric Analysis (TGA) unit. SBR samples were pyrolysed in a TGA unit in a nitrogen gas (N_2) atmosphere. The identities and absolute concentrations of over 32 major and minor species have been established, including a large number of aromatics, substituted aromatics, and PAHs. The light hydrocarbon species have also been determined simultaneously and identified as hydrogen (H_2), acetylene (C_2H_2), methane (CH_4), ethane (C_2H_6), and butane (C_4H_{10}) with lower concentrations of other hydrocarbon gases. Significant amounts of ethyl benzene, toluene, and styrene were observed between 330°C and 500°C. The largest PAH detected was the family of dibenzopyrene ($C_{24}H_{14}$) (molecular weight 302), benzo[ghi]perylene.

Luekewille, A., Bertok, I., Amann, M., Cofala, J., Gyarfas, F., Heyes, C., Karvosenoja, N., Klimont, Z., and Schöpp, W. *A framework to estimate the potential and costs for the control of fine particulate emissions in Europe.* Laxenburg, Austria, IIASA Interim Report IR-01-023, 2001.

This paper presents a methodology for estimating primary PM emissions in Europe and the costs involved to reduce these emissions from the various sources in European countries. The framework developed is compatible with existing approaches to estimate emissions and costs for sulfur dioxide (SO_2), NO_x, ammonia (NH_3), and volatile organic compound (VOC) in the RAINS model. Total suspended particulate (TSP) emissions were estimated to be similar for tire wear and road vehicle exhaust. The relative contribution of tire wear to PM10 and PM2.5 was much less than road vehicle exhaust.

Manchester-Neesvig, J. B., Schauer, J. J., and Cass, G. R. "The distribution of particle-phase organic compounds in the atmosphere and their use for source apportionment during the southern California children's health study." *Journal of the Air & Waste Management Association,* 53, 2003, 1065–1079.

Atmospheric particulate matter (PM) samples from 12 sites in southern California, collected as part of the Southern California Children's Health Study (SCCHS), were analyzed using gas chromatography/mass spectrometry (GC/MS) techniques. Ninety-four organic compounds were quantified in these samples, including n-alkanes, fatty acids, polycyclic aromatic hydrocarbons (PAH), hopanes, steranes, aromatic diacids, aliphatic diacids, resin acids, methoxyphenols, and levoglucosan. Source contributions to atmospheric PM from six important air pollution sources were quantified: gasoline-powered motor vehicle exhaust, diesel vehicle exhaust, wood smoke, vegetative detritus, tire wear, and natural gas combustion.

Overhoff, D. Tires. In *Encyclopedia of Polymer Science and Technology.* Weinheim: Wiley-VCH Verlag GmbH & Co., 2004.

Chapter describing the chemistry and manufacture of tires.

Pierson, W., and Brachazek, W. "Airborne particulate debris from rubber tires." *Rubber Chemistry and Technology,* 47, 1974, 1275–1299.

Early report on tire wear emissions PM. Only 10% of the mass of tire wear PM was present in particles smaller than 3 microns.

Rogge, W. F., Hildemann, L. M., Mazurek, M. A., Cass, G. R., and Simoneit, B. R. T. "Sources of Fine Organic Aerosol. 3. Road Dust, Tire Debris, and Organometallic Brake Lining Dust—Roads as Sources and Sinks." *Environmental Science & Technology,* 27, 1993, 1892–1904.

Particulate matter emitted to the atmosphere due to motor vehicles arises from several sources in addition to tailpipe exhaust. In this study, the organic constituents present in fine particulate (d_p less-than-or-equal-to 2.0 micron) road dust, brake lining wear particles, and tire tread debris (not size segregated) were analyzed using gas chromatography/mass spectrometry. More than 100 organic compounds were quantified in these samples, including n-alkanes, n-alkanoic acids, n-alkenoic acids, n-alkanals, n-alkanols, benzoic acids, benzaldehydes, polyalkylene glycol ethers, PAH, oxy-PAH, steranes, hopanes, natural resins, and other compound classes. To evaluate the contributions from major urban sources to the road dust complex, source profiles representing different types of vehicle exhaust, brake dust, tire debris, and vegetative detritus are compared, and their fractional contributions are estimated using several groups of organic tracer compounds.

Sarkissian, G. "The analysis of tire rubber traces collected after braking incidents using Pyrolysis Gas Chromatography/Mass Spectrometry." *Journal of Forensic Sciences,* 52, 2007, 1050–1056.

Tire marks are left due to the friction between the tire rubber and the solid road surface and do not always demonstrate the tire tread pattern but do contain traces of the tire. In this study, Pyrolysis Gas Chromatography/Mass Spectrometry was used to analyze 12 tires from different manufacturers and their traces collected after braking incidents. Tire marks were left on a conglomerate road surface with sudden braking. The samples were pyrolysed without removal of contaminant in a micro-furnace type pyrolyzer. All 12 samples were distinguished from each other and identified as coming from their original source. Additionally, components were present in the tire mark material that were not present in the tires, evidence of partial chemical transformation of the tire rubber.

Thorpe, A., and Harrison, R. M. "Sources and properties of non-exhaust particulate matter from road traffic: A review." *Science of the Total Environment,* 400, 2008, 270–282.

A review of non-exhaust PM emissions, including re-suspended dust, brake PM, and tire wear PM.

Wik, A., and Dave, G. "Occurrence and effects of tire wear particles in the environment—A critical review and an initial risk assessment." *Environmental Pollution,* 157, 2009, 1–11.

A review of non-exhaust PM emissions, including re-suspended dust, brake PM, and tire wear PM and their ecotoxicological effects.

A.2.3 Brake Emissions

Allen, T. Miller, T., and Preston, E. "Operational Advantages of Carbon Brakes." *Aero Magazine,* 35, 2009, 17–18.

The advantages of using carbon brakes instead of steel brakes on aircraft are discussed.

Blau, P. J. *Compositions, Functions, and Testing of Friction Brake Materials and Their Additives.* Oak Ridge National Laboratory, ORNL/TM-2001/64, September 2001, 9–11.

Compositions of automobile and aircraft brakes are presented.

Bukowiecki, N., Lienemann, P., Hill, M. Figi, R., Richard, A., Furgur, M., Rickers, K., Falkenberg, G., Zhao, Y., Cliff, S. S., Prevot, A. S. H., Baltensperger, U., Buchmann, B., and Gehrig, R. "Real-World Emission Factors for Antimony and Other Brake Wear Related Trace Elements: Size-Segregated Values for Light and Heavy Duty Vehicles." *Environ. Sci. Technol.,* 43, 2009, 8072–8078.

Trace element measurements were performed in an urban street canyon and next to a freeway in Switzerland. For antimony, emission factors were 11 ± 7 and 86 ± 42 μg km^{-1} $vehicle^{-1}$ for light and heavy duty vehicles, respectively.

Garg, B. D., Cadle, S. H., Mulawa, P. A., Groblicki, P. J., Laroo, C., and Parr, G. A. "Brake wear particulate matter emissions." *Environ. Sci. Technol.,* 34, 2000, 4463–4469.

A brake wear study on a brake dynamometer was performed under four wear conditions using seven brake pad formulations that were in high volume use in 1998. The study included brakes that were semi-metallic, brakes using potassium titanate fibers, and brakes using aramid fibers: 35% of the brake pad mass loss was emitted as airborne PM and 86% and 63% of the airborne PM were smaller than PM10 and PM2.5, respectively. Also, 18% of the PM emissions was carbonaceous with the rest being metallic species together with silicon, phosphorus, sulfur, and chlorine.

Gietl, J. K., Lawrence, R., Thorpe, A. J., and Harrison, R. M. "Identification of brake wear particles and derivation of a quantitative tracer for brake dust at a major road." *Atmospheric Environment,* 44, 2010, 141–146.

Size-segregated analysis of atmospheric PM sampled with micro-orifice uniform deposit impactors (MOUDI) in March 2007 in London was performed. Fe, Cu, Ba, and Sb correlated highly with road-side activity, indicative of a common traffic-related source. Barium was found in 1.1% of brake wear (PM10) particles from the traffic fleet as a whole, allowing its use as a quantitative tracer of brake wear emissions at other traffic influenced sites.

Hjortenkrans, D. S. T., Bergbäck, B. G., and Häggerud, A. V. "Metal Emissions from Brake Linings and Tires: Case Studies of Stockholm, Sweden 1995/1998 and 2005." *Environ. Sci. Technol.,* 41, 2007, 5224–5230.

PM from brake linings and tire tread rubber were measured for a select vehicle pool in Stockholm, Sweden. Brake linings were found to be the major source of road traffic emitted Cu and Sb. Tires were found to be main sources of Zn and Cd emissions in Stockholm.

Honeywell website, http://www.honeywell.com (as of August 31, 2012).

Iijima, A., Sato, K., Yano, K., Tago, H., Kato, M., Kimura, H., and Furuta, N. "Particle size and composition distribution analysis of automotive brake abrasion dusts for the evaluation of antimony sources of airborne particulate matter." *Atmospheric Environment,* 41, 2007, 4908–4919.

Abrasion dusts from three types of commercially available non-steel brake pads were generated by a brake dynamometer at disk temperatures ranging from 200–400°C. Concentrations of metallic elements (K, Ti, Fe, Cu, Zn, Sb and Ba) in the size-classified dusts were measured by inductively coupled plasma atomic emission spectrometer (ICP-AES) and inductively coupled plasma mass spectrometer (ICP-MS). The number-based mean diameter of the brake abrasion dusts was found to be between 1 and 2 μm.

Iijima, A. Sato, K., Yano, K., Tago, H., Kato, M., Kozawa, K., and Furuta, N. "Emission Factor for Antimony in Brake Abrasion Dusts as One of the Major Atmospheric Antimony Sources." *Environ. Sci. Technol.,* 42, 2008, 2937–2942.

Abrasion tests were conducted on commercially available brake pads (nonasbestos organic) using a brake dynamometer to determine the antimony (Sb) emission factor originating from automobiles. K, Ti, and Fe were determined by an inductively coupled plasma atomic emission spectrometer (ICP-AES), and Cu, Zn, Sb, and Ba were determined by an inductively coupled plasma mass spectrometer (ICP-MS).

Lough, G. C., Schauer, J. J., Park, J-S., Shafer, M. M., Deminter, J. T., and Weinstein, J. P. "Emissions of Metals Associated with Motor Vehicle Roadways." *Environ. Sci. Technol.,* 39, 2005, 826–836.

PM emissions of metals and other particle-phase species were measured from on-road motor vehicles in two tunnels in Milwaukee, Wisconsin, in the summer of 2000 and the winter of 2001. PM was collected on multiple collocated filters for mass and chemical analyses. Elemental composition of the PM samples was measured by using inductively coupled plasma mass spectrometry (ICP-MS) techniques. This study found higher OC than EC and that Sb and Cu are important indicators of brake wear. Size distributions of the metal emissions revealed that the mean size is between 1 and 10 μm.

Meggitt Aircraft Braking Systems website, http://www.meggitt-mabs.com (as of August 31, 2012).

Safran (formerly, Messier-Bugatti) website, www.messier-bugatti.com (as of August 31, 2012).

Sanders, P. G., Xu, N., Dalka, T. M., and Maricq, M. M. "Airborne brake wear debris: size distributions, composition, and a comparison of dynamometer and vehicle tests." *Environ. Sci. Technol.*, 37, 2003, 4060–4069.

Particle size distributions of light-duty vehicle brake wear debris are reported. Measurements were performed on a brake dynamometer and a test track. The number-based mean diameter of wear debris from braking events was 1–2 μm for three classes of lining materials: low metallic, semi-metallic, and non-asbestos organic (NAO). The wear rates were found to be material dependent with 3–4 times higher PM emissions observed from the low metallic linings compared with the semi-metallic and NAO linings. Elemental analysis of the wear debris reveals a consistent presence of Fe, Cu, and Ba.

Tatarzycki, E. M., and Webb, R. T. *Friction and Wear of Aircraft Brakes.* ASM Handbook Volume 18: (ASM International), 1992, 582–587.

A summary of aircraft brakes composition is presented. The brake wear PM characteristics are influenced by factors such as brake material composition, heat sink mass, energy absorbed by the brakes, surface velocity of the friction interfaces, and aircraft deceleration requirements.

Thorpe A., and Harrison, R. M. "Sources and properties of non-exhaust particulate matter from road traffic: a review." *Science of the Total Environment,* 400, 2008, 270–282.

Physical and chemical properties of brake and tire wear emissions are reviewed. Copper (Cu) and antimony (Sb) were found to be reliable tracers of the presence of brake wear particles in the urban environment, while zinc (Zn) was found to be emitted during the tire wear process. Tire wear is also an important contributor to organic aerosol.

UTC Aerospace Systems (formerly Goodrich) website, www.goodrich.com (as of August 31, 2012).

Wahlström, J., Olander, L., and Olofsson, U. "Size, Shape, and Elemental Composition of Airborne Wear Particles from Disc Brake Materials." *Tribol. Lett.*, 38, 2010, 15–24.

One pair each of low-metallic (LM) and non-asbestos organic (NAO) brake pads was tested against grey cast iron rotors. The concentration and size of airborne wear particles were measured in real time during testing. Airborne wear PM were collected on filters during the tests and analyzed using scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX). The analyzed wear PM samples contained elements such as iron, titanium, zinc, barium, manganese, and copper. Both the low-metallic and non-asbestos organic type of brake pads tested revealed a bimodal size distribution with peaks at 280 and 350 nm.

APPENDIX B

Airport Selection Process

This appendix discusses the process the project team went though to determine a preferred airport for conducting the APU, tire, and brake measurement campaign. Several factors, such as size and fleet mix, meteorology, prior experience of team members working with specific airports, and accessibility, were considered and used to down-select Chicago O'Hare International Airport as the preferred airport, which was presented to the ACRP Project 02-17 panel for its approval as part of Task 4: Interim Report.

B.1 Candidate Airports

There were several factors that were important for selecting an airport at which the team would conduct its emissions sampling and measurements. These factors included having (1) a fleet mix that would allow access to a variety of aircraft and consequently a variety of APUs, tires, and brakes; (2) an average ambient temperature range during the year to allow for testing in both low and high temperatures; (3) airport management supportive of the project and willing to allow the team to travel to several parts of the airport operating area to access equipment and emissions sources; and (4) an airport layout that would enable ready access to APU exhaust streams and, more important, an area sufficiently near an active runway to sample tire emission plumes near the touchdown portion of the runway and brake emission plumes near the deceleration portion of the runway.

The project team began with a list of eight airports to screen against these criteria. Table B.1 summarizes some of the considerations that went into making the initial list. Each airport was then screened further as described in the following subsections to arrive at a preferred airport.

B.1.1 Fleet Mix

The national fleet mix described in Appendix A, Section A.1.4, was used to evaluate the fleet mix at the candidate airports. Based on a review of this data, the project team determined that all of the large hub airports had sufficient mix of aircraft to provide ready access to the most prevalent APU models and a wide mix of aircraft tires and brakes. Oakland airport was screened out of the candidate airport list because it did not have a sufficiently broad fleet mix to satisfy the needs of this project.

B.1.2 Meteorology

Because of an interest in obtaining information on the effect of ambient conditions on the PM emissions, the measurement campaign was planned to encompass seasonal variation of ambient temperatures by choosing a cold weather winter measurement opportunity, as well as a warm weather deployment. The primary concern was to have testing opportunities spanning a wide range of ambient temperatures. This was most constraining in choosing the cold weather measurement opportunity, limiting airports to northerly situated airfields that have a wide range of airplane type usage on a regular basis. Large city airports in Northeast and northern Midwest locations were the prime candidates for the cold temperature measurements. The same airport would also serve well for a summer location for a warm temperature measurement location, but other options could be considered if required.

Table B.2 presents a summary of annual ambient temperature for the cities in which the candidate airports are located. The difference in average mean temperature between July and February illustrates the prospective temperature range for the proposed data collection.

On the basis of the average annual ambient winter/summer temperature range, Atlanta, Houston, and Oakland were screened out of the preferred airport list.

B.1.3 Previous Experience

The project team has participated in a number of NASA, FAA, DOD, and ACRP-sponsored field-testing programs and has measured engines in a variety of engine test cells and

Table B.1. Candidate airports.

Airport	Significant Considerations
Atlanta Hartsfield	Large commercial service hub airport; prior team member experience working with airport; prior team member experience working with primary carrier.
Boston Logan	Large commercial service hub airport; readily accessible to one team member; prior team member experience working with a primary carrier; reasonably large summer/winter temperature difference.
Chicago O'Hare	Large commercial service hub airport; prior team member experience working with airport; prior team member experience working with primary carrier; reasonably large summer/winter temperature difference.
Detroit	Large commercial service hub airport; reasonably large summer/winter temperature difference.
Houston Bush	Large commercial service hub airport; prior team member experience working with airport.
Minneapolis	Large commercial service hub airport; large summer/winter temperature difference.
Oakland	Medium size commercial service hub airport; prior team member experience working with airport; prior team member experience working with primary carrier.
Philadelphia	Large commercial service hub airport; prior team member experience working with airport; reasonably large summer/winter temperature difference.

airport venues. Such testing has included both sampling from stationary airplanes and from plumes advected from runways during routine operation, on a non-interference basis. The measurements to be carried out under ACRP Project 02-17 involved measurements both on stationary airplanes (APU emissions measurements) and on emissions advected from landing runways (tires and brakes).

Returning to an airport where one or more of the project team members had a relationship could expedite the planning and staging of the pilot test. Negotiating a testing program depends heavily on the team's reputation and experience and on its working relationships with the airports and airlines communities. In prior projects, the project team had successfully negotiated agreements to measure aircraft-related emissions on specific aircraft and airport facilities in Atlanta Hartsfield, Boston Logan, Chicago O'Hare, Cleveland Hopkins, Oakland International, Dallas Love Field, Chicago Midway and New York JFK. The airlines the team had worked with include Delta, Continental, Southwest, United, Continental Express and Federal Express. As a result of those prior successful negotiations, Boston Logan and Chicago O'Hare were the team's top priorities.

B.1.4 Accessibility

The project team coordinated with the selected airline/airport combination to gain the needed access for both the APU measurements and the tire and brake advected emissions measurements. For the APU measurements, the cooperating airline would be asked to operate the APU for a period on the order of 1 hour at varying operating loads, with the mobile diagnostic unit situated at the APU exhaust location. Setting up the sampling probe and preparing to take the measurement should be accomplished in significantly less than 1 hour, followed by a testing period of up to 1 hour. The team anticipated that 5 to 6 APUs could be measured during one night's access to the required number of aircraft.

For the brake and tire emissions measurements, the project team required access to locations on the downwind side of a landing runway, as close to the runway as safe and practical from an airport operational perspective. Two separate locations would be needed: one close to where touchdown typically occurs and one in the area where brakes are typically applied, further along the runway from touchdown. Ideally, the mobile lab could be driven from one location to the other under airport traffic control without crossing active traffic routes. A sampling line could be used to extend a probe closer to the runway from the mobile lab if the mobile lab was constrained to be further from the runway than was considered optimal. An example of a runway that might afford sufficient access without conflicting with other runways or taxiways was the new North Runway at Chicago O'Hare.

Table B.2. Airport annual ambient temperature.

													Range
Atlanta	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	July-Feb
Avg. High	50	55	64	72	78	85	88	87	81	72	64	54	
Avg. Low	31	34	42	50	58	66	68	68	64	51	42	35	
Mean	41	45	54	62	68	76	78	78	74	62	54	45	33
Boston	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Avg. High	35	37	45	55	66	76	81	78	72	62	52	40	
Avg. Low	21	24	31	40	48	58	65	64	56	46	38	26	
Mean	28	30	38	48	58	68	74	72	65	55	45	34	44
Chicago	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Avg. High	31	35	46	58	70	80	84	82	76	65	50	36	
Avg. Low	17	22	31	41	51	60	66	65	58	47	36	24	
Mean	25	28	38	50	61	71	75	74	68	56	44	30	47
Detroit	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Avg. High	30	34	44	57	68	78	84	81	74	61	48	35	
Avg. Low	18	20	28	38	50	58	65	64	56	45	35	24	
Mean	25	27	37	48	60	68	74	72	65	54	42	30	47
Houston	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Avg. High	61	65	72	78	84	88	92	92	88	81	72	64	
Avg. Low	42	45	52	60	67	72	74	74	71	61	52	45	
Mean	52	55	64	70	76	81	84	84	80	71	64	55	29
Minneapolis	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Avg. High	20	26	38	56	68	78	84	80	70	58	41	25	
Avg. Low	2	8	22	36	47	57	64	60	50	38	25	10	
Mean	12	18	31	46	58	68	74	71	61	48	34	18	56
Oakland	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Avg. High	57	60	62	66	68	72	74	75	76	72	64	57	
Avg. Low	40	42	44	44	47	51	52	54	54	50	45	40	
Mean	48	52	54	55	58	62	64	65	65	62	55	48	12
Philadelphia	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Avg. High	37	41	51	62	74	81	86	84	77	66	55	44	
Avg. Low	22	24	34	42	52	61	67	66	58	46	37	28	
Mean	30	34	42	52	64	72	77	76	68	56	46	36	43

B.2 Airport Short List

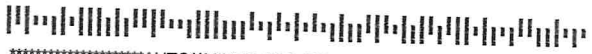
Based on the factors previously described, the project team selected Chicago O'Hare as the preferred airport and United Airlines as the preferred airline to work with on this project. When the team met with the ACRP Project 02-17 panel to discuss the project interim report, Chicago O'Hare was proposed and accepted by the panel. If for some reason, Chicago O'Hare had not worked out as a suitable location for this campaign, the project team would have approached Boston Logan Airport and Delta Airlines to host this project.

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation

TRANSPORTATION RESEARCH BOARD
500 Fifth Street, NW
Washington, DC 20001

ADDRESS SERVICE REQUESTED



**********AUTO**MIXED ADC 207
1038/ AC97 / 1
MR. FRANK VOZEL
ARKANSAS STATE HIGHWAY AND TRANSPORTATION DEPARTMENT
PO BOX 2261
LITTLE ROCK, AR 72203-2261

456

Non-profit Org.
U.S. Postage
PAID
Merrifield, VA
Permit No. 2333

NATIONAL ACADEMY OF SCIENCES
1863-2013 • Celebrating 150 Years of Service to the Nation

THE NATIONAL ACADEMIES™
Advisers to the Nation on Science, Engineering, and Medicine

The nation turns to the National Academies—National Academy of Sciences, National Academy of Engineering, Institute of Medicine, and National Research Council—for independent, objective advice on issues that affect people's lives worldwide.
www.national-academies.org

ISBN 978-0-309-28371-7
90000
9 780309 283717